The Impact of Smart Meters on Residential Water Consumption: Evidence from a Natural Experiment in the Canary Islands

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Abstract

Smart meters can promote behavioral changes and water conservation by improving information and providing feedback about water consumption to households. In this paper, we evaluate a large-scale programme implemented by the municipal water company of La Laguna (Tenerife). Exploiting quasi-experimental variation brought about program, we estimate the effect of water meter replacement on measured water consumption and the behavioral effect of the installation of the smart metering technology allowing households to access daily water consumption and real-time feedback through an online portal. Our main empirical analysis employs a difference in differences identification strategy and uses annual consumption data from 51,674 households observed over 10 years. We find a positive effect of water meter replacement on measured water consumption. Our main finding is that providing access to the smart metering technology induces households to reduce consumption by around 2% on average. Our results point to consumers' engagement with the information portal as the main mechanism behind the observed behavioral response.

Keywords: water conservation, behavioral change, smart meter, natural experiment
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1. Introduction

Water is a key natural resource for the development of a country or region. Therefore, efficient use of water is crucial to promote sustainable development through better health, food and environmental quality (Rieckmann 2017). There is an increasing concern that traditional freshwater sources are under stress and competing uses are growing around the world. Moreover, climate change impacts raise additional concerns, threatening the security of water supply in areas as Southern Europe and its islands (Jorda-Capdevila et al. 2019, Ludwig et al. 2011). This could hinder economic growth, spur massive migration flows, and spark conflict development (Nurse et al. 2014). To mitigate these issues, an efficient distribution and usage of water is crucial.

First, the precise monitoring of water consumption through the usage of modern, non-defective, water meters is essential to improve efficiency of water distribution and evaluate the effectiveness of demand management strategies. Although metering companies often claim that water meters fail to register all water passing through as they age, no study has provided evidence about the effect of meter replacement on measured water consumption. Such evidence would be policy relevant. In fact, even though investing in metering technology is costly for utilities with constrained budgets, it could be beneficial if it allowed to register more water and enabled a better management through earlier leak detection. Second, research in psychology and behavioral economics has shown that the consumption of natural resources is affected by behavioral anomalies in individual decision making, such as, e.g., limited knowledge of prices and quantities consumed, rational inattention and status quo bias (Allcott et al. 2014). These anomalies might keep consumers from maximizing their material interests (Frederiks et al. 2015). Also in the water sector, households may have imperfect information on price and level of consumption, preventing them from investing in water-saving devices or changing behavior to optimize water consumption.

To promote household water conservation, distribution companies have implemented demand management strategies based on price as well as behavioral interventions (Lu et al. 2019, Pérez-Urdiales & Baerenklau 2019). In Europe, the most common demand management strategy has been based on price interventions such as the introduction of increasing Block Tariffs (EEA 2017). However, the empirical studies indicate that the water demand tends to be price inelastic (Olmstead et al. 2007, Worthington & Hoffman 2008, Reynaud 2015). Therefore, pricing policies may have limited effect in curbing residential water consumption. In this context, some water distribution companies introduced behavioral interventions aimed at increasing the level of information about price, consumption and the negative impact on the environment of consumption habits. Clearly, behavioral interventions based on the provision of different types of information such as norm-based or consumption-based information can be seen as a complement to pricing measures.

In this paper, we investigate the effect of smart metering on water consumption. Specifically, we ask two questions: (i) what is the "mechanical" effect on water consumption of replacing old meters with new water meters?; (ii) does providing access to enhanced information and real-time feedback on water use influence consumers behavior? If so, what are the mechanisms behind the behavioral response?

To answer these questions, we evaluate a large scale program implemented by the municipal water company of La Laguna (Tenerife, the Canary Islands) to promote an efficient use of water. The program has been implemented in two steps: (i) a staggered roll-out of a new digital water meter; (ii) in a later phase implemented among households equipped with the new water meter, a staggered installation of an antenna allowing access to smart metering features. Specifically, the installation of the antenna allows consumers to access almost real-time information on water consumption, as well as to set alarms indicating when consumption reaches a certain predefined level, through an online portal (i.e., "smart metering").[1] The utility informed its customers about both the upcoming installation of a new

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[1] In the rest of the paper, with "smart meter" we indicate a digital water meter on which an antenna has been installed allowing households to obtain advanced almost real-time information on water consumption through an online portal.

meter as well as the installation of the antenna (i.e., access to smart metering features) with two separate letters delivered to the households' residence.

Our identification strategy exploits the quasi-experimental variation in treatment status (for both the installation of the new water meter and antenna) across households and over time brought about the program. While the new digital water meters were distributed to different households over time based on the age of the old meter, the distribution of the antenna has been implemented based on the location of the water meter in the customers' residence (i.e., a time-invariant individual characteristic.) We adopt two empirical strategies to estimate the effect of the new digital meters on *measured* water consumption and the behavioral effect of providing the possibility to access the enhanced information about water consumption through the online portal.

First, we use an event-study research design to estimate the effect of the new digital meters on water consumption. This exploits the fact that different households receive the installation of the new meter at different points in time. We then estimate water usage as a function of the distance in time to the installation of the new digital water meter, conditioning on individual and year fixed effects.

Second, we adopt a difference in differences approach to estimate the effect of informing households (equipped with a new digital meter) about the possibility to access enhanced information on water consumption and real-time feedback through the online portal. We then exploit the variation across households and over time in the installation of the antenna. We use households that received the new digital meter but did not receive the antenna, as a control group for the behavior of those households that can access enhanced information on their water consumption. Because treatment status is assigned by the utility based on time-invariant factors (the position of the water meter in the households' residence) that are potentially correlated with water consumption, with condition our empirical analysis on individual fixed effects. Further, we restrict the sample to observations corresponding to households observed after the installation of the digital meter to isolate the hypothesized “behavioral” consumers response from the “mechanical” effect of meter replacement. Using information on consumers’ engagement with the information portal, as well as data on the automatic alarms indicating when consumption reaches a certain predefined threshold set by consumers, we then provide suggestive evidence about the mechanisms behind the behavioral response.

Our empirical analysis uses water consumption data on 51,674 households observed between 2010 and 2019, provided directly by the utility. First, we provide evidence of a substantial positive effect of water meter replacement on *measured* water consumption. Following the substitution of an old water meter with a new one, *measured* water consumption increases on average by around 6 percent relative to the year before the installation of the new meter. This result then supports the claim that, as they age, water meters indeed fail to register all water actually used by consumers.

Second, our results show that providing access to smart metering features such as real-time feedback on water consumption and notifications about water use induce a substantial behavioral response of households. Specifically, we find that, overall, households reduce water consumption by around 2 percent on average following the installation of the remote reading features that allow to access the enhanced information about water consumption. This results should be interpreted as intention-to-treat effect of the combination of sending the letter informing about the installation of the smart meter and the availability to access the smart metering features through the online portal. Our results also show that the intervention induces a permanent reduction in water use, while providing support to the validity of the common trend assumption. Further, we provide suggestive evidence that the main mechanism through which the installation of the smart meter affects households response is the usage of the online portal, rather than the simple nudge coming from receiving the letter. Finally, we document a stark difference in the response of small and large users to the availability of the smart metering technology, with large users driving the overall reduction in water consumption.

Related literature Feedback information to households about the consumption of natural resources has received increasing attention. The impact of information provided through the installation of smart meters has been studied mainly in the context of energy consumption (see, e.g. Jessoe & Rapson 2014). In particular, providing households with information about their energy consumption or savings has proved to alter consumers decision-making (Abrahamse et al. 2005, Bager & Mundaca 2017, Darby 2010, Delmas et al. 2013, Ehrhardt-Martinez et al. 2010, Karlin et al. 2015).

Few works are analyzing the impact of smart meters on residential water consumption.[2] For instance, Fielding et al. (2013) ran a randomized control trial to measure the long-term impact of three different trials on household water consumption in Queensland (Australia). They trialed three opt-in methods of reducing residential water demand: information on how to save water in the household, information about social norms involving water conservation and, finally, feedback to individual households about their overall and specific water use using smart meters. Compared to the control group, all three voluntary trials were effective in reducing household water use. Also, in Australia, Davies et al. (2014) investigate a water utility trial involving 630 households in Sidney during a year, examining the impact of trial technology on short and long-term water consumption compared to a matched control group. Households with IHDs reduced consumption by an average of 6.8 % when compared to the control group (over 5 years). Tiefenbeck et al. (2013) focus on the interplay between water and energy savings, exploring behavioral spillovers and moral licensing. They report a controlled field experiment at a multifamily residence with a reduction of an average of 6 % of water consumption of the trial group relative to the control group during the trial period. The trial consists of providing weekly feedback through a door flyer (200 apartments) and measures consumers' response to the community's lower water use.

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[2] In the literature, it is possible to find studies, although few, on the impact of other types of information treatments on water consumption. For instance, Ferraro & Price (2013) analyzed the impact of several information treatments using data from a conservation experiment with more than 100000 households performed in Atlanta in 2007. Their results show that norm-based information such as social comparison of consumption has a higher impact than providing technical advice. See Fletcher (2017) for a review of these studies.

However, previous evidence shows that more information might not necessarily induce a reduction in water consumption. For example, Wichman (2017) shows that the increase in billing frequency may increase overall water consumption. He exploits a natural experiment to find out that low users increased their consumption by a greater proportion than the reduction made by higher users, which results in a significant overall 3.5-5% increase in water consumption. The author argues that the behavioral change caused by more frequent information is due to improved price perception and consumer attention. Brent & Ward (2019) show that some consumers overestimate the water price and increase water consumption after learning the true water costs. In addition, the results in Attari (2014) show that consumers underestimate water use. Moreover, Wichman (2014) and Brent & Ward (2019) show that consumers respond to the average price and not to the marginal price, so that consumers choices are suboptimal in the presence of nonlinear pricing.

Nearly all the studies that aim at analyzing the effect of smart meters on water consumption are either based on small sample data or lack a formal identification strategy. The main contribution of this work is that of estimating the impact of smart meters on residential water consumption using a large panel dataset and adopting a rigorous identification strategy. Our results complement previous findings in the literature about the reduction in water consumption due to the installation of a smart meter. We also provide suggestive evidence that the effect on water consumption is driven by the behavioral change induce through the usage of the online portal. These results show that more information can induce an overall reduction in water consumption when delivered through an online portal, as opposed to when it is delivered through higher billing frequency, as shown by Wichman (2017). Further, to the best of our knowledge, this is the first study that provides evidence of the effect of substituting old water meters with new ones on measured water consumption. This paper contributes to the public policy debate about the effectiveness of demand-side management measures in reducing water demand in the residential sector.

The rest of the paper is organized as follows. Section 2 describes the quasi-experimental setting we exploit for identification. In Section 3 we discuss our identification strategies. Section 4 presents the data and describes the empirical strategy. In Section 5 we present the empirical results. Section 6 concludes.

2. The water smart meter program

The program has been carried out by the water utility company Teidagua SA, a public-private partnership (PPP) created to supply water services to the municipalities of La Laguna and Tacoronte (Tenerife, Spain). The water distribution network of Teidagua supplies approximately 69,000 customers in the city of La Laguna.

The program was implemented in two steps. First, starting from 2010, the company began to substitute each year a part of the old water meters with new digital water meters.[3] By 2019, the replacement had been carried out for 60 percent of total residential customers. The users received a letter from the supplier (see Figure A1 in Appendix A) notifying them about the replacement of the old meter with a new digital meter. The replacement decision was decided exclusively based on the age of the old meter. All geographical service areas of the company in La Laguna municipality were involved in this program (see Figure B1 for a graphical representation of the spatial implementation).

In a later, second step, the company introduced a staggered roll-out of antennas (i.e., "smart metering") on the digital water meters installed during the first phase of the programme.[4] These antennas allow for almost real-time feedback information on household water consumption through an online portal. Further, they allow to set alarms indicating

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[3] The reading accuracy of water meters is determined by the pressure in the network and the meter's age. The new digital meter allows accurate measurements from very low flow rates up to peak flows. Therefore, any water supplier is interested in replacing old and imprecise water meters for economic reasons with new and more accurate meters (Fontanazza et al. 2013).

[4] Notice that the new digital water meter distributed in the first step can be installed with or without an antenna. Only 1.3% of households that received a new digital meter in a given year, also received the installation of the antenna in the same year. This installation was implemented only if the meter was located outside of the house in order to guarantee the remote transmission of the data through the antenna (see Figure B2 for a graphical representation of the spatial implementation). The second stage started in July 2012, but only 89 installations were completed until 2015.

if the water consumption reaches a pre-defined level. Households can access such remote reading features by registering to the online portal.[5] By 2019, smart meters were installed to around 30 percent of total domestic consumers of La Laguna. For a given household, the median time between the installation of the digital meter (first step) and the installation of the additional antenna (second step) was three years. The distribution of new digital meters and smart meters installations over time is reported in Figure 1.

Also in this case, the consumers received a letter from the utility (see Figure A2 in Appendix A) announcing the installation of the antenna and informing about the possibility to access enhanced information on daily water consumption through an online portal as well as the opportunity to set an alarm to receive notifications when the water consumption reaches a certain predefined threshold. The letter was sent to each household at the time of installation of the smart metering technology (i.e., antenna), at different times depending on when the installation was implemented. Unlike the first letter, consumers were informed about the advantages of the new meter in reducing water consumption.

Metering companies often claim that old water meters tend to under-report water consumption, this way undermining the efficiency and financial sustainability of water distribution. For this reason, in this paper, we test the policy-relevant hypothesis that the meter replacement induces an increase in the *measured* water consumption.

The installation of the smart meter might influence households' behavior with respect to water consumption in at least three ways: (i) the letter that customers receive at the time of installation of the antenna might nudge individuals towards a higher water consumption awareness; (ii) individuals might access the online portal and have additional information allowing them to optimize their water consumption; (iii) increased attention to water con-

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[5] Importantly, all customers of the water utility can register to the same online portal, regardless of the presence of the antenna. Without the antenna, all customers can find out about the existence of the online portal by navigating through the company's website, which is in turn indicated in all communications (e.g., periodic billings) from the water utility. No separate letter has been received by non-antenna customers about the online portal. However, while access to the online portal with the antenna allows almost-real time information on household water consumption and to set alarms, without antenna the customer can only access historical bills and consumption through the online portal (i.e., the same information they receive with their periodic bills).

sumption when a notification about water use exceeding a predefined threshold is received. The possible change in water consumption may be achieved through water conservation behavior or investment in water-saving devices. In this paper, we test the hypothesis that smart metering affects water consumption through at least one of these three ways.

3. Identification

3.1 Effect of installing new water meters

The first goal is to estimate the "mechanical" effect of the new digital water meters. We employ a within-household event-study design to estimate the effect of installing the new meter on measured water consumption.[6] The event study approach allows to trace out the full dynamics of the effects, and allows to exploit individual-level variation in the timing of the meter replacement.

In our setting, the event is defined as a household receiving the new digital water meter in a given year. We exploit the staggered distribution of the new meters, with different households receiving the installation of the new meters in different years. We condition on individual fixed effects to control for unobserved time-invariant selection into treatment as well as year fixed effects. The control group for a household receiving a new digital meter in a given year consists of households who receive the same digital meter in some other year.[7] The identifying assumption is that the timing of the installation is not systematically related to water consumption, once we condition on individual and year fixed effects.

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[6] We choose not to adopt a difference in differences identification strategy, in which also households that never receive a new meter in the observation period are included a control group, because of the treatment assignment based on the age of the old meter at the time of replacement (as described in Section 2). The group of households that do not receive a new meter during the observation period indeed does not represent a good control group (i.e., for the counterfactual behavior of those that do receive a new meter during the observation period) because they are already equipped with substantially more recent water meters.

[7] We also restrict the sample to observations within ten years from and to the installation of the new meter.

3.2 The effect of allowing access to the smart metering features

Our main objective in this paper is to estimate the causal effect of informing households about the possibility to access enhanced information and real-time feedback on water consumption. To this end, we adopt a difference in differences (DID) identification strategy.

We then exploit the quasi-experimental variation in the installation of the antenna on the new digital meters, with a group of the households receiving the additional antenna in different years and another group of households that did not receive the possibility to access the enhanced information. To disentangle the possible hypothesized "behavioral" consumers response of the letter informing about the possibility to access the enhanced information from the "mechanical" effect of the water meter replacement, we restrict the sample for this analysis to observations corresponding to households observed after the installation of the new digital meter.

The water utility assigned the installation of the antennas on the digital water meters based on the position of the meter in the households' residence (garden, entrance etc.). Because treatment is assigned by the utility based on (time-invariant) factors that are potentially correlated with water consumption, conditioning on a group level (treatment status based on the presence of smart water meter) may yield biased estimates for the effect of the smart meters. To overcome this potential threat to identification, we condition our analysis on individual fixed effects. This will also account for potential selection (driven by company's choices with respect to the distribution of the smart metering features) due to other (time-invariant) households' and residences' characteristics influencing water consumption.

As a control group for the households that are informed about the possibility to access enhanced information on their water consumption in a given year, we use households that received the digital meter but do not receive the antenna in the observation period. Further, the control group includes households receiving the same additional antenna in some other year. To avoid potential issues related to different age distributions of water meter age between households that do receive an antenna and households that never receive it, we condition our analysis also on age of the meter fixed effects. The key identifying assumption in this context is that within-household changes in water consumption for households that received a smart meter would have been the same as those of households that never received a smart meter (or received the smart meter in some other year), in the absence of the smart meter installation. We perform standard parallel trend tests and placebo tests to lend support in favor of the validity of this assumption.

This DID strategy allows us to identify the intention to treat (ITT) effect, that is the effect of the letter informing about the *possibility* to access the enhanced information on water consumption, independently of whether households actually access such information through the online portal or not. To gain some insights about whether the information provided through the information portal is the key channel behind the observed effect, we exploit the (time-invariant) information about whether households did register to the online portal (and set alarms informing them about consumption reaching certain thresholds). In particular, we employ a DID strategy similar to that used to identify the ITT effect described above, in which we restrict the estimation sample to households that registered to the online portal (both receiving and not receiving the letter). In this analysis, we use households that received the digital meter, registered to the online portal but did not receive the additional antenna, as a control group for the households that registered to the online portal and received the letter about the possibility to access enhanced information on their water consumption. Clearly, because the decision of registering to the online portal is endogenous, this strategy can only provide suggestive evidence about the underlying mechanisms behind the identified ITT effect.

4. Data and empirical strategy

We use data from the population of residential customers in the utility area of Teidagua. The data is an unbalanced panel of 51,674 households observed between 2010 and 2019.[8] 37,751 households (around 73 % of the sample) received a new digital meter between 2010 and 2019. 19,569 households (around 38 % of the sample) also received the letter informing them about the installation of the antenna that gives access to the enhanced information and real-time feedback on water consumption. Among the households that received an antenna in the observation period, 11,054 households were registered to the online portal (around 57%) in 2019. Around 21% of households that did not receive the informational intervention (and did not receive the antenna) were registered to the online portal in the same year. Finally, around 74% of the households that registered to the online portal also set an alarm that would notify them when their water consumption reaches a predefined level.

The estimation of the effect of replacing the old meter with the new ones uses the sample of 37,751 households that receive a new digital meter between 2010 and 2019.[9] We use the sample of 51,674 households equipped with water meters allowing for the installation of the remote reading antenna to estimate its effect on water consumption.[10]

The data include information on annual water consumption in m^3, the year in which the current meter was installed (together with meter-specific information such as brand and model number) and whether (and when) the household received the letter informing them of the installation of the additional antenna allowing to access enhanced information. Further, the data include time-invariant information about whether the household has registered to the online portal (measured in 2019), set the alarm using the online portal and regional

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[8] We exclude from the sample used for the analysis the observations corresponding to households that have a water meter that does not allow for the possibility of installing the additional antenna for the remote reading features, or whose model type is unknown. This sample selection drops around 20% of the overall population in the utility area of Teidagua.

[9] As explained below, we keep observations corresponding to households observed five years before and after the event (i.e., the installation of the new meter in a. given year).

[10] For this second analysis, we drop observations corresponding to observation-year before the installation of the current digital meter.

indicators of the households' residence.

All data were provided directly by the water supplier. Households in the sample consume on average around 103 m^3 of water per year. Households that receive the antenna and hence the smart metering features consume on average, after the installation of the digital meter and before the installation of the antenna, around 98 m^3 of water per year. Households that never receive the antenna (our control group in the identification strategy for the effect of the smart meter) consume on average, after the installation of the digital meter, around 101 m^3 of water per year.

4.1 Graphical evidence

To provide a first insight on the source of variation we exploit to identify the effect of the new meters installation and the letter on water consumption, we start providing descriptive evidence about the evolution of water consumption over time by treatment status.

First, in Figure 2.a we plot average water consumption over time, for cohorts of households that received the new meter in different years (2014, 2015 and 2016). The graph shows that, while before the installation of the new meter water consumption seemed to be decreasing over time for the three cohorts, we observe an increase in water consumption between the year before and after the installation of the new water meters. The event-study design graph in Figure 2.b, plotting average water consumption against the distance in years to meter replacement, also shows an increase in water consumption around the time of the new meter installation of around $5m^3$. The decrease in water consumption as the meter ages (for distance in years to meter replacement between -5 and -1, as well as between 1 and 5) is consistent with the idea that current water meters tend to measure a smaller amount of water as they age. The two graphs provide then first suggestive evidence about the positive effect of replacing old meters with new ones on the *measured* water consumption. We wish to stress that the evidence in Figure 2.b is merely suggestive of the implications of installing the new meter on water consumption, in that it does not allow to disentangle between "event time" effects and pure time effects. As described in Section 3.1, we take care of this issue in our event study analysis below.

The graphs in Figure 3.a and 3.b compare the evolution of water consumption over time for households that receive the letter informing about the remote reading in 2015 and 2016, respectively, with that of households that never receive the information letter. The graphs show that the evolution of water consumption between treated and control households starts to diverge when treated households receive the information letter. Specifically, treated households seem to increase water consumption less then households that do not receive the letter following the intervention.

4.2 Empirical specification

In this section we describe the empirical strategies that follow from the identification strategies discussed in section 3.

To estimate the "mechanical" effect of installing the new digital water meters, we estimate the following regression model:

$$y_{it} = \beta_0 + \sum_{j=-5}^{+5} \beta_j TI^M_{i,t+j} + \lambda_i + \delta_t + \epsilon_{it} \tag{1}$$

where the subscripts i and t refer to households and year, respectively, y is the outcome of interest, and $TI^M_{i,t+j}$ (j=-5, -3, ... +5, with -1 the omitted category) are event-time indicators, i.e., a set of dummy variables that capture the distance in years before and after household i received the new water meter.[11] Because we omit the dummy variable indicating the year prior to the event, $TI^M_{i,t-1}$, all effects on water consumption β_j (j=+1, +2, ... +5) are relative to the year before the installation. λ_i includes a set of individual (time-invariant) fixed effects, δ_t is a period fixed effect common to all households, and ϵ_{it} is the usual idiosyncratic error term. We estimate the model using household water consumption (in m^3) as dependent

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[11] The dummy indicators $TI_{i,t+j}$ are defined to take value one if household i received the new meter in $t-j$.

variables. Because some household-year observations have zero water consumption, our preferred specification uses water consumption in m^3. Our coefficients of interest β_j (j=-5, -4, ... +5) indicate the water consumption j years before or after the installation of the meter, relative to the year before the installation. This regression model is estimated using the sample of households that received a new digital meter between 2010 and 2019. We cluster standard errors at the household level.

The identification strategy discussed in Section 3.2 for the average effect of receiving the information about the online portal yields the following *canonical* specification of the difference in differences regression model:

$$y_{it} = \beta_0 + \beta_1 SM_{it} + \gamma AM_{i,t} + \lambda_i + \delta_t + \epsilon_{it} \tag{2}$$

where SM_{it} is a dummy indicating if the household i has a smart meter installed in period t, $AM_{i,t}$ is a full set of age of the meter fixed effects, which we include to control for different consumption patterns due to meter-aging effects, and all other variables are as in (1). Our coefficient of interest is β_1, capturing the average effect of informing households about the possibility to access enhanced information and real-time feedback on water consumption. We estimate the model using household water consumption (in m^3) as dependent variable. The price of water does not appear in eq. (2) because all households face the same pricing in a given year.[12] The estimation uses the sample of households equipped with a meter that allows for the installation of the antenna observed between 2010 and 2019. The inclusion of the observation-year in which the household receives the letter (and the antenna) would attenuate the estimated effect. For this reason, we exclude from the estimation sample the transition years (i.e., those observations corresponding to the year in which the household receives the letter). As for the estimation of eq. 1, we cluster standard errors at the household level.

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[12] During the period of the analysis, only a price change for all customers has been introduced by the water company in 2013. The effect of this price change is captured by the year fixed effects.

Further, to support the validity of the common trend assumption, as well as to explore possible long-run effects of smart metering on water consumption, we estimate the following *dynamic* specification of the difference in differences model:

$$y_{it} = \beta_0 + \sum_{j=-4}^{+3} \beta_j TI^S_{i,t+j} + \gamma AM_{i,t} + \lambda_i + \delta_t + \epsilon_{it} \tag{3}$$

where all variables besides $TI^S_{i,t+j}$ are as in (3). $TI^S_{i,t+j}$ (j=-4, -3, ... +3, with -1 the omitted category) are now a set of dummy variables that capture the distance in years before and after household i received the letter informing about the possibility to access enhanced information about water consumption.[13] An importance difference compared to the estimation of eq. (1) is that the sample for the estimation of eq. (3) includes also households that are never treated, as control group. Hence, all effects on water consumption β_j (j=-4, -3, ... +3) are relative to the year before the smart metering installation and the behavior of the households that never receive the additional antenna. Support to the validity of the parallel trend assumption would come from finding no differences in water consumption between households with and without smart meter before the installation of the smart meters ($\beta_j = 0$ for all $j < 0$.).

5. Main results

5.1 The effect of installing new water meters

The estimates of the within-household event-study regressions for the effects of the new meter installation, controlling for year and individual fixed effects, are reported in Table C.1 in Appendix.[14] Figure 4 presents our preferred event study estimates, obtained adjusting

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[13] The dummy indicators $TI^S_{i,t+j}$ take value one if household i received the letter in $t - j$.

[14] A complete description and discussion of the results from the baseline specification (1) for water in m^3 (reported in Column 1 of Table C.1) is included in Appendix C.

water consumption (in m^3) for pre-trend (Column 2 of Table C.1).[15] The graph shows small (and not always significant) estimates for the years before households receive a new meter, and a jump in water consumption starting in the year in which households receive a new meter. Specifically, we find an increase in *measured* water consumption following the installation of around 6 percent, that seems to remain rather stable between 1 and 4 years after the installation. The estimate for the year in which households receive a new meter is around 3 percent, reflecting the fact that the new meter starts measuring water some time during that year.

Is the 6 percent increase in measured water consumption, at the time of new meter installation, a plausible estimate for the effect of installing the new meter? Our data show that one additional year in meter age is associated with -0.6m^3 of measured water on average.[16] Further, consider that the source of variation we exploit at the "event", consisting in the installation of the new meter, is the exogenous decrease in meter age. Hence, since old meters in our sample are replaced every 8 years on average, a back-of-the envelope calculation would suggest an average increase in water consumption due to the installation of a new meter of around 5% (8 years * 0.06%).

5.2 The effect of allowing access to smart metering features

We start our investigation of the effect of providing access to enhanced information and real-time feedback about water consumption on households behavior by estimating the effect of letter (and installation of the additional antenna for the remote reading). We thus exploit our difference in difference identification strategy described in section 3.2.

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[15] Because pre-trends in water consumption due to the aging meter (even after conditioning for year fixed effects) may confound the breaks around the new meters installation, we follow Kleven et al. (2019) and estimate the main event study regression residualizing the outcome variable using the estimated linear pre-trend (estimated using only pre-event data). We convert the estimated level effects into percentages using the predicted counterfactual outcome in the absence of the new meter installation.

[16] See Appendix C for details on how we obtain this estimate and additional empirical evidence supporting the hypothesis that meters do not measure all water passing through as they age. This evidence is consistent with the technical decay due to meter aging estimated using engineering approaches (Couvelis & Van Zyl 2015, Johnson 2019).

Column (1) of Table 1 reports the estimation results of eq.(2), using water consumption in m^3 as dependent variables. Our results show that receiving the letter induced a substantial behavioral response of households, using a linear specification. Specifically, we find that households decreased annual water consumption by around 1.8 cubic meters (Column 1) on average following the installation of the smart meter. This corresponds to a decrease in water consumption of approximately 2%, considering the average water consumption. We can interpret this estimate as the decrease in water consumption due to households' behavioral responses since the measurement of water consumption is obtained using the same meter before and after the installation of the antenna that allows the smart metering features. We can then rule out that the effect we measure is confounded with differential measurements due to technical factors.

As discussed above, the credibility of these estimates as causal effects of the installation of the remote reading features relies on the validity of the parallel trend assumption. To provide evidence in support of this assumption, we conduct two tests. First, we estimate the dynamic specification of the difference in differences model (3) to show that, before the information treatment, the trends in water consumption had been the same for households that eventually received the smart meter and households that did not. We estimate this equation using our preferred linear specification.

The results of this parallel trend test are reported in Figure 5. The Figure reports point estimates for the differences in water consumption between households with and without information treatment at a certain distance to the time of the intervention, relative to the year before the installation of the smart meter (β_j in eq. 5). The graph provides clear evidence that the trends in water consumption were parallel between treated and control households in the pre-treatment period. Further, it shows how the change in water consumption happens when the smart meter feature becomes available.

The results of the dynamic DID also show that the informational intervention induced a permanent reduction in water use, with the estimated effects β_j that remain rather constant (for $j>0$) up to three years after the information treatment. This points towards a permanent behavioral shift in water use due to the availability of enhanced information through the online portal.

Second, to lend further support to the validity of our estimates as causal effects of providing remote reading feature, we perform placebo tests. We assign the treatment (i.e., households receive the letter and the antenna is installed) before the actual smart meter installation and keep only households that never received the smart meter or treated households before they received the letter and had access to the the smart metering features. We then estimate eq. (2) and test the significance of the coefficient associated with SM_{it} to detect potential differences in the trend of consumption between treated and control households before the actual installation of the smart meters. The results of this test are reported in Table 1. Columns (2), (3) and (4) report the estimation results when the placebo treatment (access to smart metering features) is assigned 2, 3 and 4 years earlier than the actual assignment, respectively. All the estimates for the placebo treatments are not significant. These results provide additional evidence that the trend in water consumption was parallel before the installation of the smart metering between treated and control households, and thus further support to the validity of our identification strategy.

5.3 Behavioral channels

We have shown that the information treatment consisting of informing the households about the possibility to access enhanced information about water consumption had a substantial impact on households water use. However, the results presented so far are still silent with respect to the mechanisms behind the observed effects. In this section, we explore which mechanism, hypothesized in Section 2 is driving the results.

In particular, to disentangle between the effect on conservation due to the provision of enhanced information and real-time feedback from the behavioral nudge from the letter, we start by estimating eq.(2) separately for those that registered to the online portal and for those that never did. Clearly, only households that registered to the online portal can access the enhanced information and real-time feedback features that the additional antenna allows to obtain. We exploit in particular the fact that it was possible for households to register to the online portal also in the absence of the additional antenna (in this case, standard information on water bills are available to the users), as described in Section 2. As we discussed in Section 3.2, because customers self-select into registering in the online portal, this strategy can only provide suggestive evidence about the underlying mechanisms. However, non-antenna households who register in the online portal consume very similar levels of consumption (112 m^3) of non-antenna households who do not register in the portal (111 m^3) in 2019 (the year in which we observe who chose to register). Further, we do not find differences in consumption between the two groups when we regress water consumption on a dummy indicating whether the household was registered in the online portal in 2019, meter age fixed effects, year fixed effects and a set of controls including regional indicators of the households' residence (see the results in Column (2) of Table C.2).

The estimation results of eq.(2) for the group of households that never registered to the online portal are reported in Column (1) of Table 2, using water consumption in m^3 as outcome variable. Column (2) shows instead the results obtained estimating the DID specification on the sample of those that registered to the online portal. The results provide a clear picture: while the information treatment has no effect on water consumption among those that never registered to the online portal (and hence, do not have access to daily water consumption or real-time feedback), it induces a large behavioral response among households that register to the online portal. In particular, households that are registered to the online portal reduce water use, following the installation of the additional antenna, by almost 7 cubic meters yearly. Although the registration to the online portal is clearly a household choice, and then these results should not be interpreted as causal estimates of accessing enhanced information or having real-time feedback, they provide suggestive evidence that the intervention induced water conservation by providing more real-time feedback, rather then by the simple nudge offered by the letter.

Further evidence about the main mechanism behind the observed effects comes from exploiting data about whether households that are registered to the online portal also set an alarm that notifies them about water consumption reaching a predefined threshold. We first estimate eq.(2) on the sample of households that registered to the online portal using only households that set the alarm as treatment group (results in Column 3 of Table 2), and then using only households that did not set the alarm after the registration as treatment group (results in Column 4 of Table 2). In both cases, we use households that never received the remote reading features but registered to the online portal as control group. The results of this analysis provide clear (though only suggestive) evidence that the introduction of the smart metering feature had an impact on water consumption mainly through the usage of the online portal and, specifically, through allowing households to receive notifications when water consumption reaches undesired levels. Indeed, while the installation of the antenna has a negative but not statistically significant effect for treated households that did not set an alarm, the remote reading features installation reduced water consumption by almost 8 m^3 among households that did set the alarm.

5.4 Heterogeneous effects: pre-treatment water consumption

Finally, we wish to explore whether large and small water users respond differently to the provision of smart metering. To this end, we estimate eq. (2) separately for households below and above the median of water consumption in the pre-treatment period.[17]

The results reported in Table 3 show a stark difference in the response of small and large water users to the availability of the remote reading features. Households consuming below-median water before the treatment respond to the installation of the antenna by increasing water consumption by around 5.5 m^3 of water. In contrast, large water users

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[17] This corresponds to entire sample for households that never receive the smart meter and observations corresponding to the years before the treatment for those households that eventually receive the remote reading features.

decrease water consumption by around 13.5 m^3 following the installation of the remote reading features. The latter result is consistent with the idea that large users are those that can, ex-ante, benefit financially the most from enhanced information on their water consumption. Further, the positive effect of smart metering among small users is consistent with the findings in Wichman (2017), suggesting that small users tend to increase water consumption when provided with more information.

6. Conclusions

In this paper, we evaluated the "mechanical" effect of replacing old meters with new water meters on *measured* water consumption and the behavioral effect of providing access to the smart metering technology, using data from the population of customers of a water utility in the Canary Islands.

We find a positive effect of water meter replacement on *measured* water consumption and a negative effect of providing access to the smart metering technology on water use. Our finding that *measured* water consumption increases following meter replacement supports the claim that, as they age, water meters indeed fail to register all water actually used by consumers. It is policy relevant because it suggests that investing in metering technology, though costly, can be beneficial for utilities with constrained budgets.

Our main finding is that enabling consumers to access real-time information and to receive notifications about water use induces them to reduce water consumption on average by around 2%. Importantly, this result should be interpreted as the intention-to-treat effect of informing about the installation of the smart metering technology and providing the possibility to access the smart metering features through the online portal. Further, we show that this effect is mainly driven by the consumers' engagement with the online portal, rather than the simple nudge coming from receiving the letter. These results have important policy implications. Considering the increasing water scarcity and then the necessity to curb water consumption around the world, these findings highlight that providing consumers with the possibility to access enhanced information through smart meters can help achieve the desired goals of water conservation.

In this work, we provided evidence of the causal effect of water meter replacement and the intention-to-treat effect of providing access to the smart metering technology. We can only provide suggestive evidence about the mechanisms behind the estimated behavioral response of households. This descriptive evidence may suggest the usage of default registrations to online portals at the time of smart metering installation as a tool to increase the effectiveness of this type of interventions. Future research should focus on identifying and estimating the effect of consumers' engagement with the online platforms through which the information is provided, and conduct a comprehensive cost-benefit analysis for the provision of smart meters.

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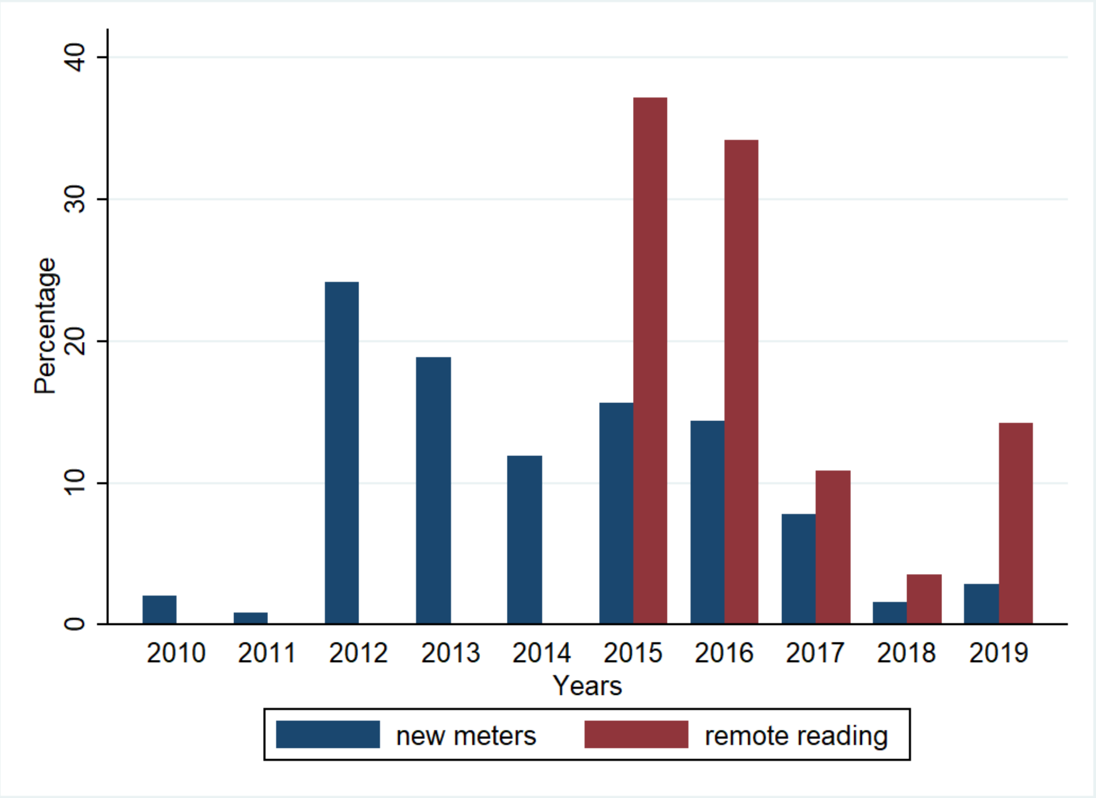
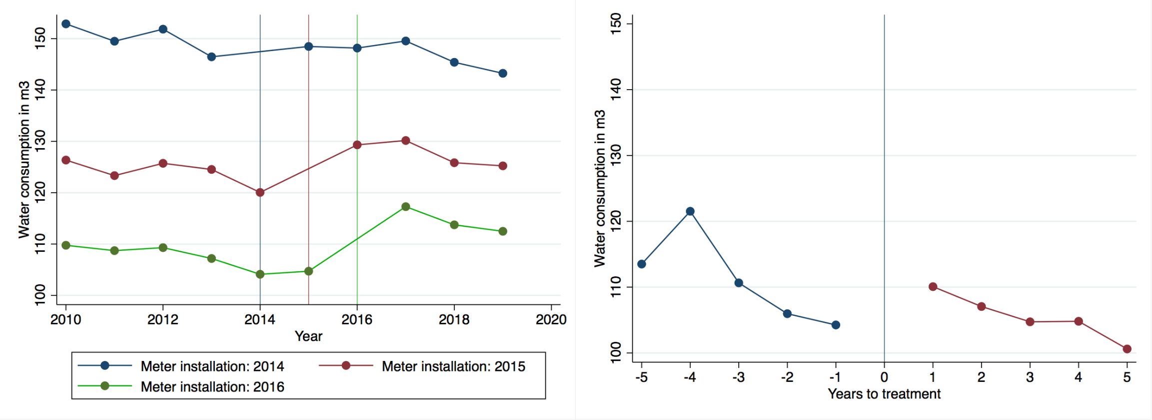


Figure 1: Distribution of new digital meters and smart meters installations over time.



(a) By year of meter replacement (b) By distance in years to meter replacement

Figure 2: Water consumption over time by year of meter replacement

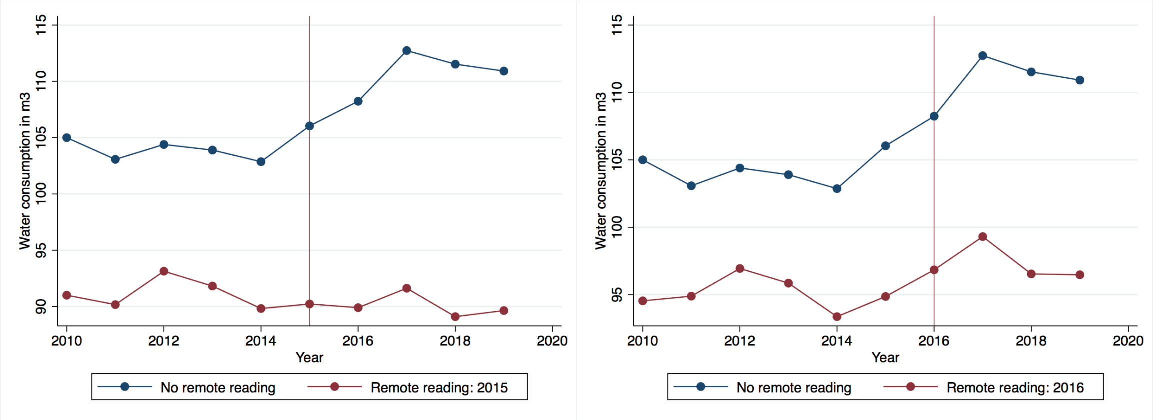


Figure 3: Water consumption over time by year of remote reading installation

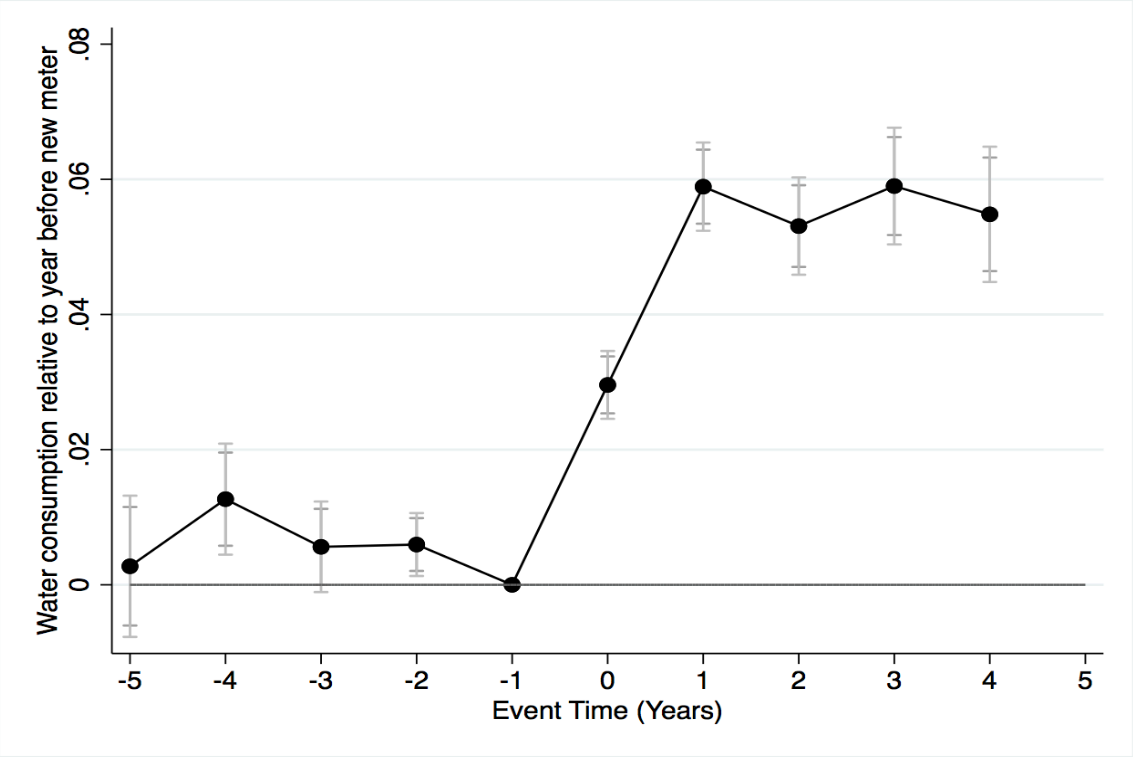


Figure 4: Event-study estimates for the effect of the new digital meter installation. Notes: Graphical illustration of the event-study estimates (eq. 1) using water consumption in m^3 as the outcome variable and controlling for pre-trend. The estimated level effects in Column 2 of Table C.1 have been converted into percentages using the predicted counterfactual outcome in the absence of the new meter installation. The horizontal axis shows the distance in years between the observation year and the installation of the smart meter, with 0 indicating the first year after the treatment. 95% and 90% confidence intervals are reported.

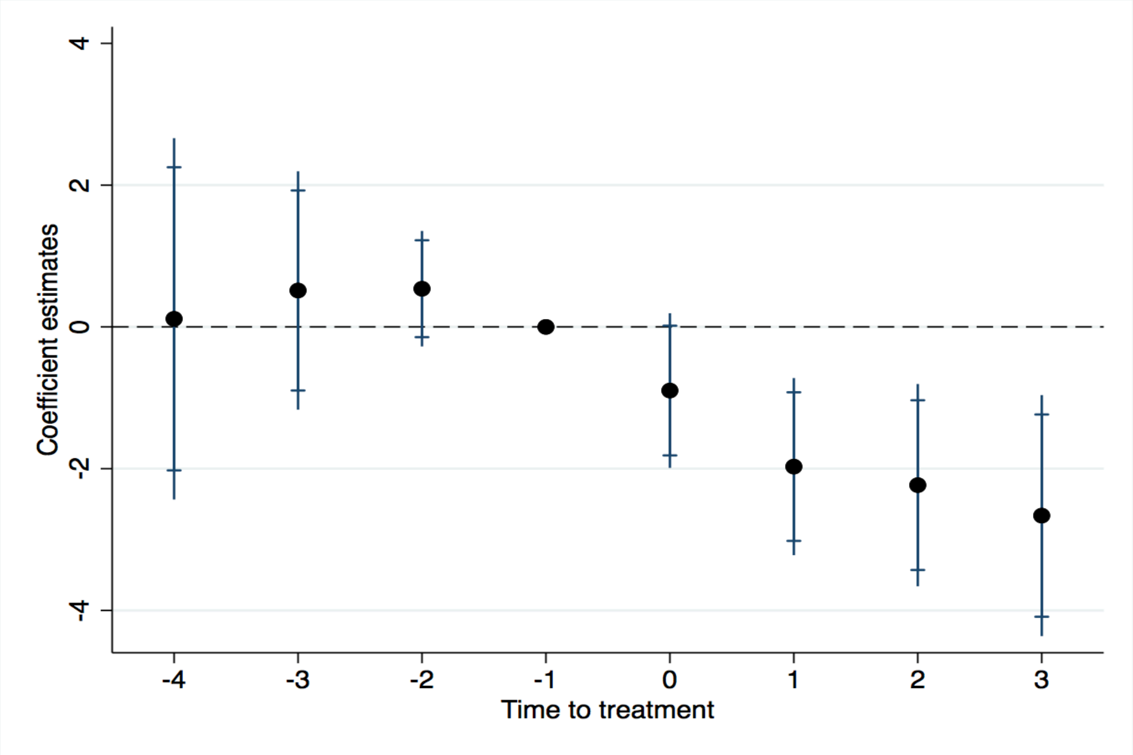


Figure 5: DID estimates for the effect of allowing access to smart metering features. Notes: Graphical illustration of the difference in differences estimates (eq. 3). Estimates for β_j are indicated on the vertical axis, with β_-1 the coefficient associated with the time to treatment period used as a reference. The horizontal axis shows the distance in years between the observation year and the installation of the antenna, with 0 indicating the first year after the treatment. 95% and 90% confidence intervals are reported.

Table 1: Intention to treat: Effect of providing access to enhanced information through remote reading

	Water consumption (in m3)			
	ITT	Placebo treatment		
		-2 years	-3 years	-4 years
	(1)	(2)	(3)	(4)
SM	-1.826***	0.067	0.790	1.180
	(0.584)	(0.430)	(0.801)	(1.068)
Age of the meter FE	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	304691	252900	252900	252900

Note: Dependent variable is water consumption in cubic meters. Column (1): DID estimate for the effect of allowing access to the smart metering features. Columns (2), (3) and (4) report the results of a placebo test that consists in assigning treatment status two years, three years and four years before the actual treatment, respectively. Three stars indicate statistical significance at the 1 % level, two stars at the 5 % level and one star at the 10 %.

Table 2: Channels: effects by registration to online portal and alarm setting

	Not registered	Registered		
		All	No alarm set	With alarm set
	(1)	(2)	(3)	(4)
SM	0.577	-6.832***	-1.079	-8.402***
	(0.832)	(1.012)	(1.628)	(1.053)
Age of the meter FE	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	198948	105743	77172	99540

Note: Dependent variable is water consumption in cubic meters. Three stars indicate statistical significance at the 1 % level, two stars at the 5 % level and one star at the 10 %.

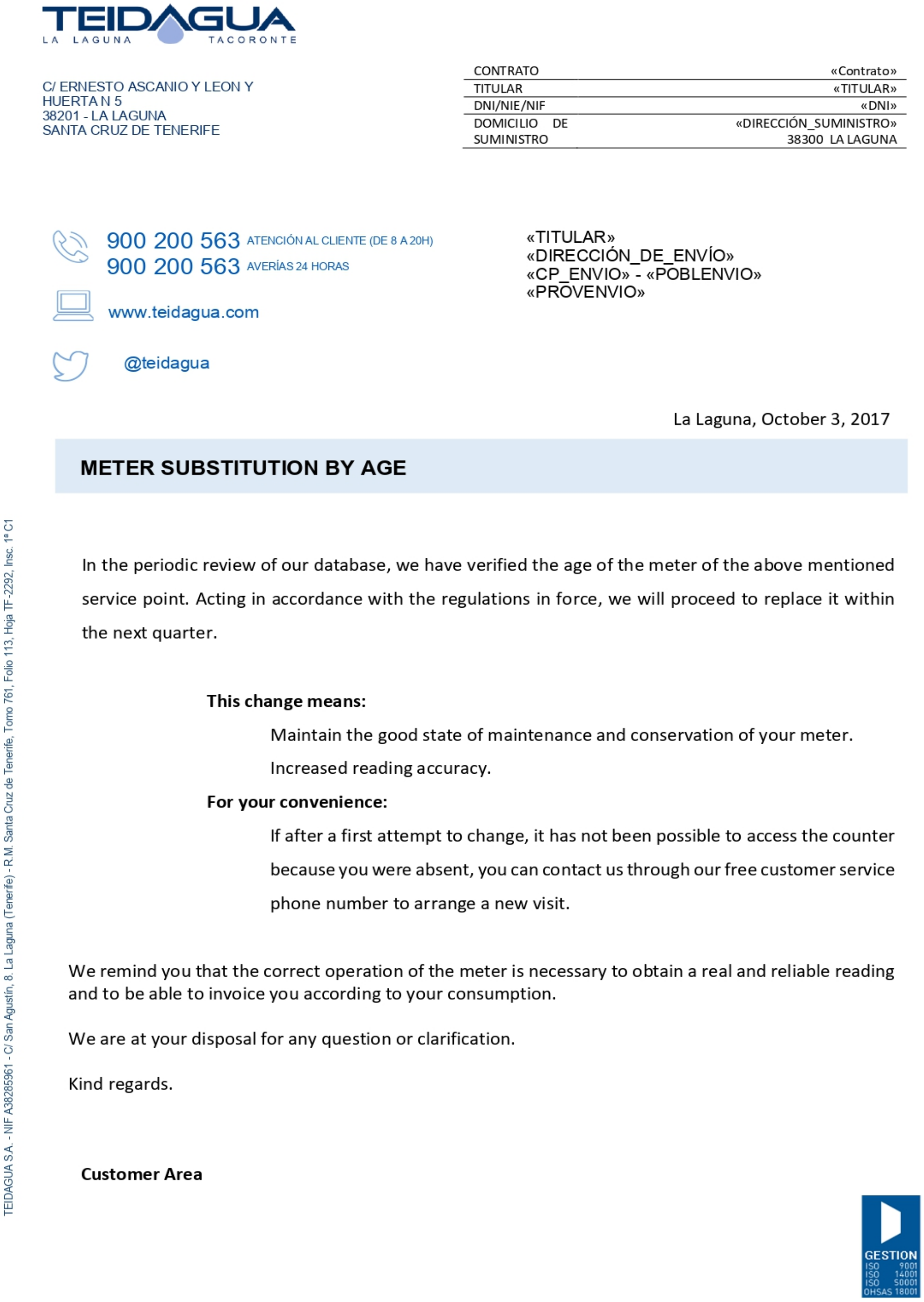
Table 3: Intention to treat: heterogeneous effects by pre-treatment consumption

	Below median	Above median
	(1)	(2)
SM	5.543***	-13.492***
	(0.613)	(1.004)
Age of the meter FE	Yes	Yes
Individual FE	Yes	Yes
Year FE	Yes	Yes
N	153167	146301

Note: Dependent variable is water consumption in cubic meters. Three stars indicate statistical significance at the 1 % level, two stars at the 5 % level and one star at the 10 %.

Appendix - For Online Publication

A. Letters sent to households



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«CP_ENVIO» - «POBLENVIO»
«PROVENVIO»

La Laguna, October 3, 2017

METER SUBSTITUTION BY AGE

In the periodic review of our database, we have verified the age of the meter of the above mentioned service point. Acting in accordance with the regulations in force, we will proceed to replace it within the next quarter.

This change means:

Maintain the good state of maintenance and conservation of your meter.

Increased reading accuracy.

For your convenience:

If after a first attempt to change, it has not been possible to access the counter because you were absent, you can contact us through our free customer service phone number to arrange a new visit.

We remind you that the correct operation of the meter is necessary to obtain a real and reliable reading and to be able to invoice you according to your consumption.

We are at your disposal for any question or clarification.

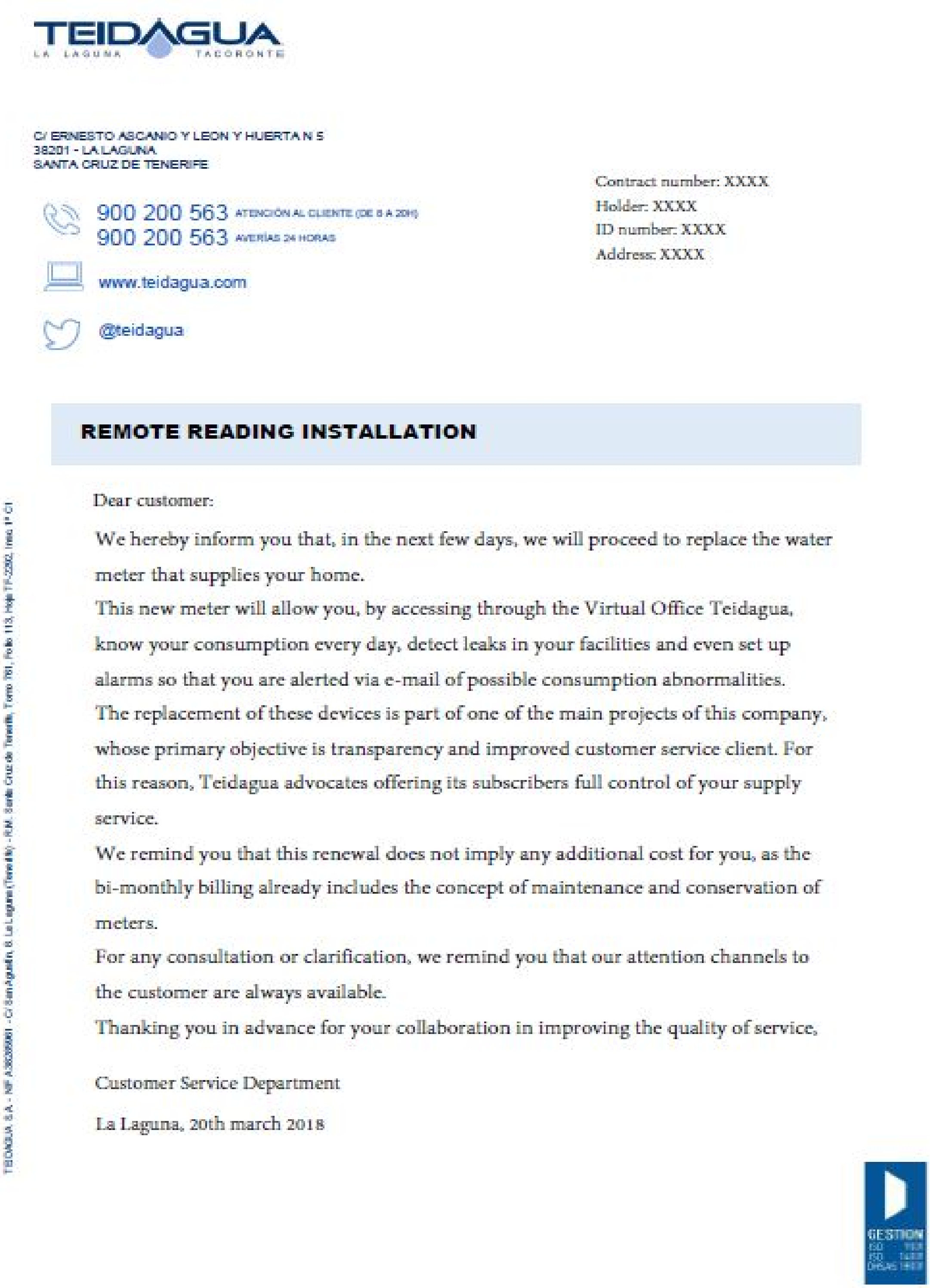
Kind regards.

Customer Area

TEIDAGUA S.A. - NIF A38285961 - C/ San Agustín, 8. La Laguna (Tenerife) - R.M. Santa Cruz de Tenerife, Tomo 761, Folio 113, Hoja TF-2292, Insc. 1ª C1

GESTION
ISO 9001
ISO 14001
ISO 50001
OHSAS 18001

Figure A.1: Letter sent to users informing about old meter replacement



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Contract number: XXXX
Holder: XXXX
ID number: XXXX
Address: XXXX

REMOTE READING INSTALLATION

Dear customer:

We hereby inform you that, in the next few days, we will proceed to replace the water meter that supplies your home.

This new meter will allow you, by accessing through the Virtual Office Teidagua, know your consumption every day, detect leaks in your facilities and even set up alarms so that you are alerted via e-mail of possible consumption abnormalities.

The replacement of these devices is part of one of the main projects of this company, whose primary objective is transparency and improved customer service client. For this reason, Teidagua advocates offering its subscribers full control of your supply service.

We remind you that this renewal does not imply any additional cost for you, as the bi-monthly billing already includes the concept of maintenance and conservation of meters.

For any consultation or clarification, we remind you that our attention channels to the customer are always available.

Thanking you in advance for your collaboration in improving the quality of service,

Customer Service Department

La Laguna, 20th march 2018

Figure A.2: Letter sent to users informing about remote reading installation

B. Geographical distribution of new meters and smart metering over time

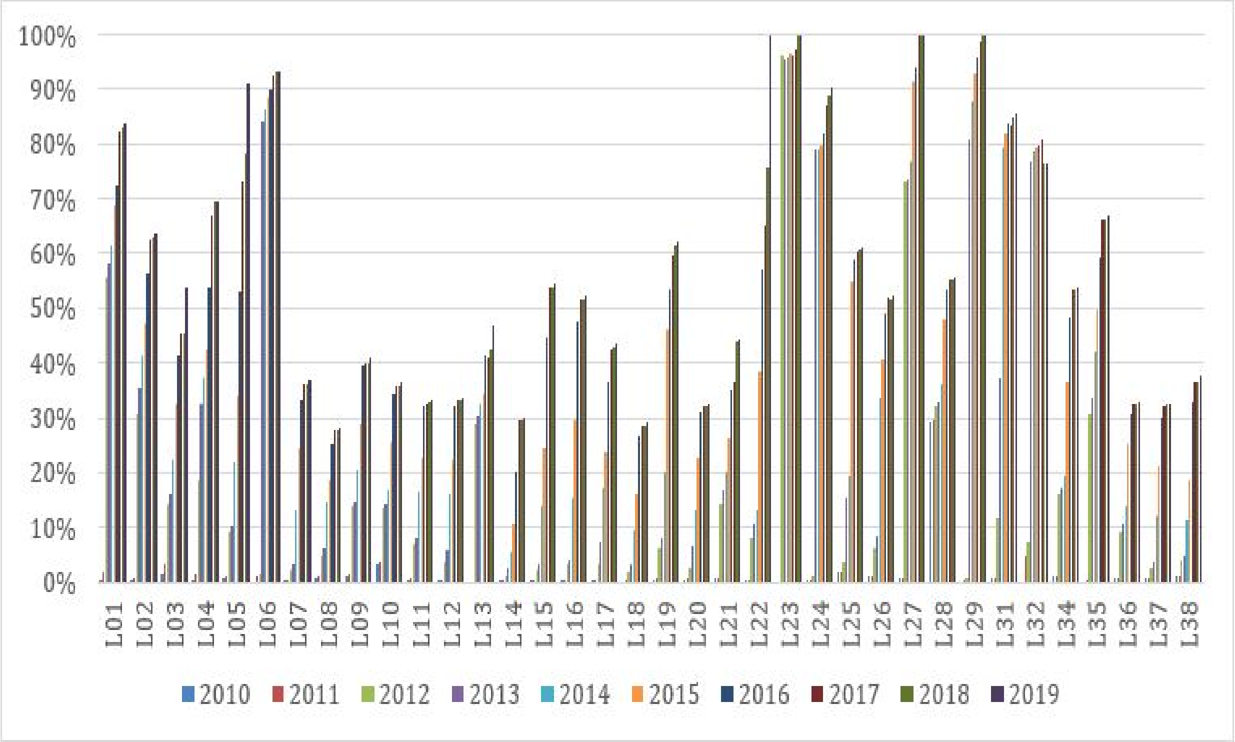

Figure B.1: Cumulative distribution of new meters installation over time by area

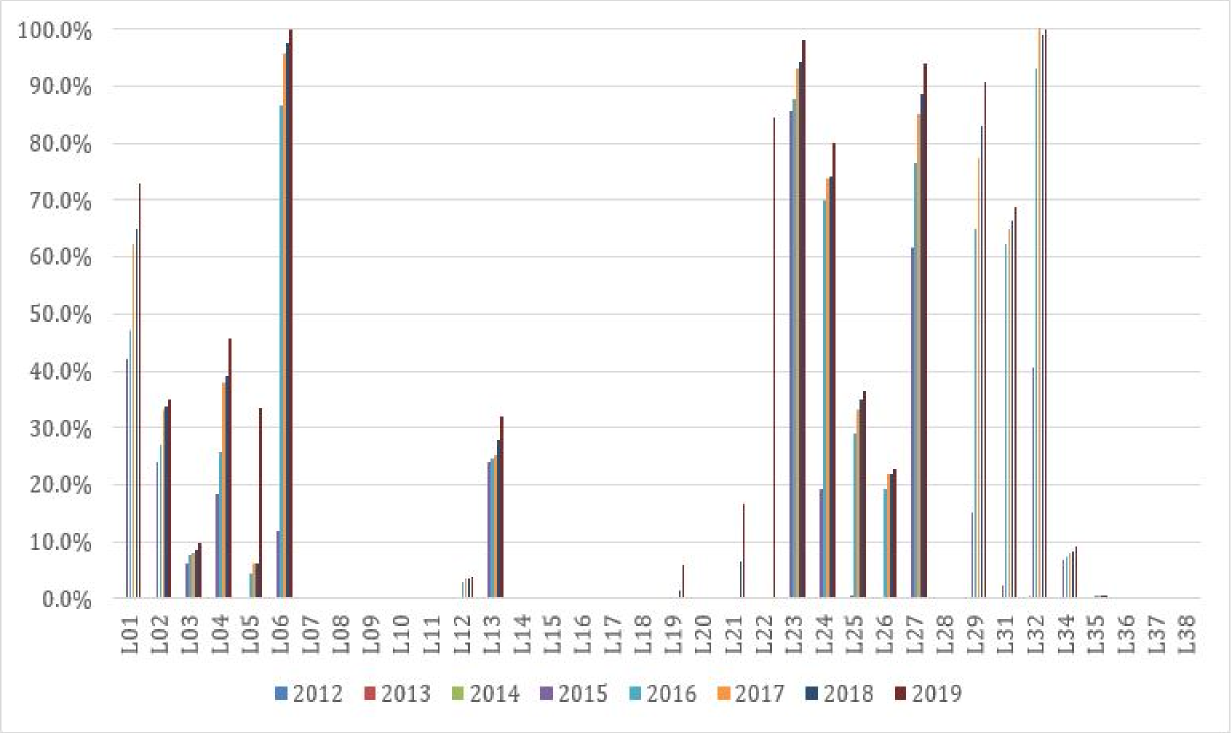

Figure B.2: Cumulative distribution of smart meter installation over time by area

C. Additional results

Table C.1 reports the estimates of the within-household event-study regressions for the effects of the new meter installation. Columns (1) reports results from the baseline specification (1) for water in m^3.

The results in Column (1) show a negative trend in "event time" conditional on year fixed effects, which is consistent with a decline in water consumption as the old meter ages, before the "event" (i.e., the installation of the new meter). The plot of average measured water consumption by meter age (see Figure C.1 in Appendix) as well as the results of a fixed effect regression of water consumption on meter age and year fixed effects (see Column (1) of Table C.2 in Appendix) both provide evidence in support of a decrease in measured water consumption as the meter age. The fixed effect estimate for the effect of meter age on measured water (-0.6m^3 per year) is close to that implied by the non-parametric event study specification, and consistent with the technical decay due to meter aging estimated using engineering approaches (Couvelis & Van Zyl 2015, Johnson 2019). Specifically, the estimates of the event time dummies before the installation of the new meter (-5 to -2) in Column (1) of Table C.1 suggest a trend in event time of around -0.5 m^3 of measured water on average per year. These results are consistent with engineering analysis estimating a linear relationship between meter age and under-registration, with an annual technical decay in measured water by meters in the range 0.4-0.7% (Couvelis & Van Zyl 2015, Johnson 2019). Taken together, this evidence provides support for the hypothesis that meters do not measure all water passing through as they age. Further, the results in Column (1) of Table C.1 show a jump in water consumption in the years following meter replacement. One year after the installation of the new meter (event time = +1), we find an average increase in measured water of around 5m^3, compared to the year before the replacement.

Columns (2) reports results from the baseline specification (1) for water in m^3, after adjusting for pre-trends. These results are reported in Figure 4 and discussed in the main text.

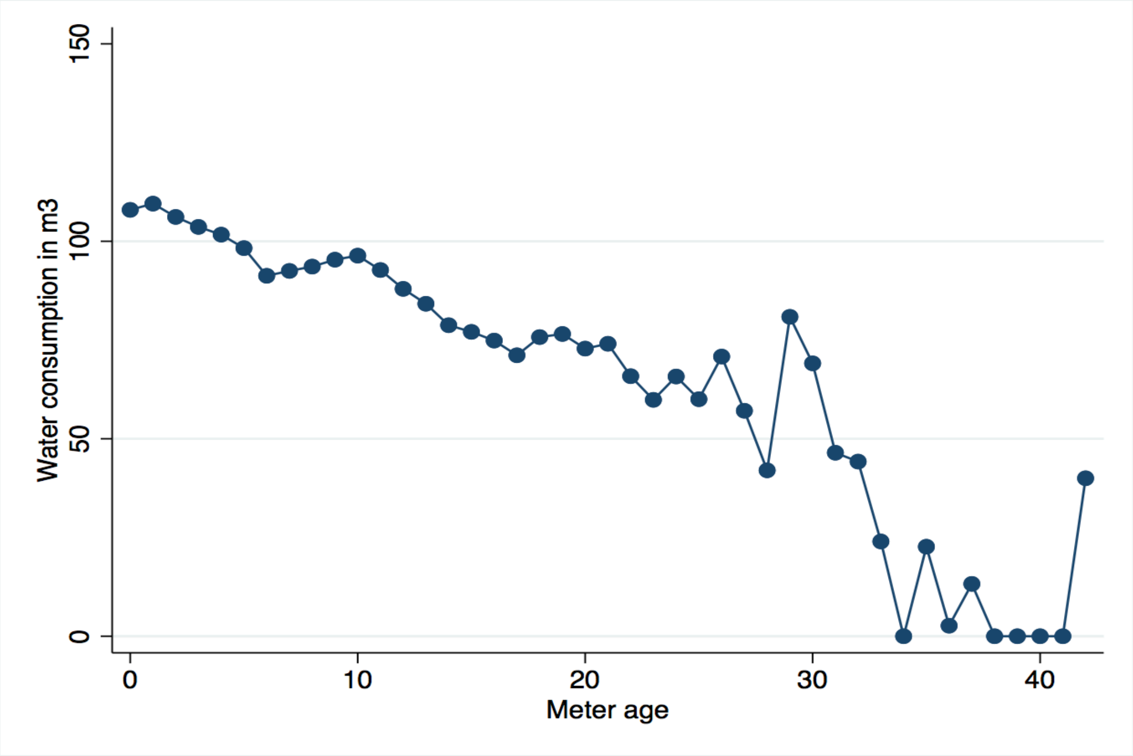

Figure C.1: Water consumption across the meter age distribution

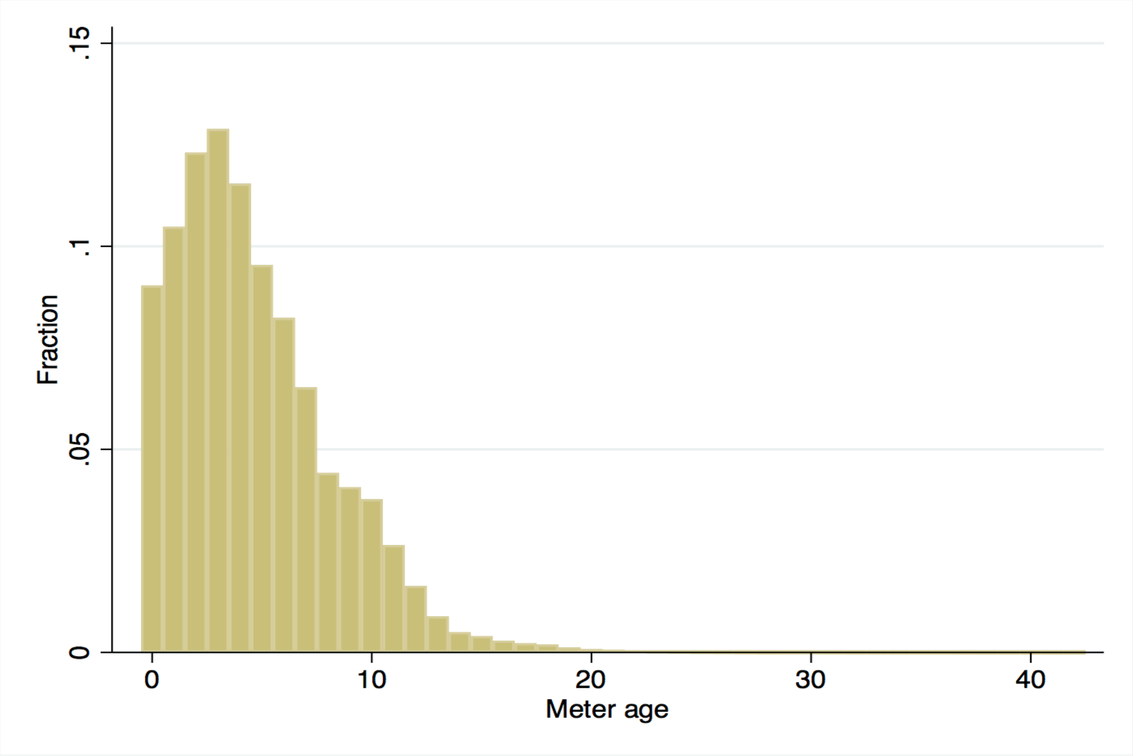

Figure C.2: Meter age distribution in the sample

Table C.1: Event study estimates: impact of new meter installation on measured water consumption

	Water (in m3)	
	(1)	(2)
Event -5	2.733***	0.302
	(0.587)	(0.587)
Event -4	3.314***	1.491***
	(0.493)	(0.493)
Event -3	1.823***	0.608
	(0.370)	(0.370)
Event -2	1.228***	0.620**
	(0.247)	(0.247)
Event +0	2.485***	3.093***
	(0.268)	(0.268)
Event +1	4.939***	6.155***
	(0.348)	(0.348)
Event +2	3.678***	5.501***
	(0.381)	(0.381)
Event +3	3.678***	6.109***
	(0.456)	(0.456)
Event +4	2.564***	5.603***
	(0.522)	(0.522)
Event +5	2.786***	6.432***
	(0.583)	(0.583)
Individual FE	Yes	Yes
Year FE	Yes	Yes
Pre-trend adj.	No	Yes
N	324499	324499

Note: Event study estimates based on eq. 1. The event is to receive a water meter replacement. Dependent variable is water consumption in cubic meters. Three stars indicate statistical significance at the 1 % level, two stars at the 5 % level and one star at the 10 %.

Table C.2: Additional results: water consumption, meter age and online portal for non-antenna users

	Water (in m3)	
	(1)	(2)
Meter age	-0.607**	
	(0.298)	
Registered in online portal		-0.364
		(0.642)
Other controls	No	Yes
Age of the meter FE	No	Yes
Individual FE	Yes	No
Year FE	Yes	Yes
N	55313	269653

Note: Dependent variable is water consumption in cubic meters. Three stars indicate statistical significance at the 1 % level, two stars at the 5 % level and one star at the 10 %.