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Water Conservation and the Common Pool Problem: Can Pricing Address FreeRriding in Residential Hot Water Consumption?

Mikael Elinder, Xiao Hu and Che-Yuan Liang

Research Institute of Industrial Economics
P.O. Box 55665
SE-102 15 Stockholm, Sweden
info@ifn.se
www.ifn.se

Water conservation and the common pool problem: Can pricing address free-riding in residential hot water consumption?* ∀

Mikael Elinder§
Xiao Hu#
Che-Yuan Liang&

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Abstract: Water is an increasingly scarce resource. It is often distributed such that consumers do not face any marginal cost of consumption, creating a common pool problem. For instance, tenants in multi-family buildings can often consume both hot and cold water at zero marginal cost. Using high-frequency data over many years, we analyze how the introduction of apartment-level metering and billing (IMB) affects hot water consumption. We find that introducing a marginal cost, reflecting the market price, decreases consumption drastically by 26%. Hence, price interventions can curb free-riding behavior and help the conservation of cheap but precious resources. Our results also show that heavy water users in the top consumption quartile account for 72% of the reduction. Moreover, cost-benefit calculations indicate that IMB for hot water is a cost-effective policy tool for reducing water and energy consumption.

Keywords: Residential water consumption, water conservation, common pool problem, free-riding, individual metering and billing

JEL classification: D12, Q21, Q25, Q28

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§ Department of Economics at Uppsala University, and Research Institute of Industrial Economics (IFN); e-mail: mikael.elinder@nek.uu.se

Department of Forest Economics and Center for Environmental and Resource Economics (CERE) at Swedish University of Agricultural Sciences (SLU), SE-90183, Umeå, Sweden; e-mail: xiao.hu@slu.se

& Institute for Housing and Urban Research (IBF) and Department of Economics at Uppsala University, SE-75120, Uppsala, Sweden; e-mail: che-yuan.liang@ibf.uu.se

1. Introduction

Access to clean water for everyone is one of the United Nation's 17 global development goals for year 2030. However, according to the World Health Organization, 785 million people do not have access to even basic drinking-water services around the world. Climate change, population growth, urbanization, and pollution will further increase water scarcity. By 2025, half of the world's population is projected to live in water-stressed areas. Intergovernmental Panel on Climate Change (2021) predicts that climate change will increase the frequency and intensity of agricultural and ecological droughts. Even in a developed country like Sweden with plenty of fresh water sources, climate change exacerbates water shortage, and water management becomes increasingly important. For instance, the unusually hot and dry summer in 2018 strained the water supply system. Facing water shortages, many municipalities enacted a series of conservation policies, such as prohibiting irrigations and launching information campaigns urging the households to save water. Moreover, one third of household water consumption consists of hot water. Heating water requires substantial amounts of energy contributing to environmental damages including emissions of greenhouse gases. Reducing such emissions is key in mitigating climate change and its consequences. Hence, eliminating wasteful consumption of both cold and hot water is an important policy goal.

A contributing factor to overconsumption of water is that water is often distributed such that households or firms do not face the full marginal cost. For instance, in Sweden, many apartments in multi-residential buildings split the bill such that each apartment can use both cold and hot water at a fixed cost independent of consumption. Because a household's consumption will incur external costs on others, private incentives differ from collective incentives. Economic theory predicts that the tenants will free-ride on each other and excessively use water. Such behavior leads to the tragedy of the commons (Hardin, 1968), which is a central problem for resource conservation. Much of recent research has focused on climate change (e.g., Greenstone et al., 2013) and pollution (e.g., Muller et al., 2011). Like clean air, fresh water is a relatively cheap but precious and increasingly scarce resource that is often free or provided at a price below the long-run marginal cost of supply (Olmstead and Stavins, 2009).

In this paper, we analyze the extent of free-riding when there is no marginal cost attached to using a relatively cheap resource. We do so by studying the effect of introducing individual metering and billing (IMB) on residential consumption of hot water. With IMB, each household faces a positive marginal cost reflecting the market price.

Due to technological advances during the last decades, IMB has become cheaper to implement and therefore increasingly popular. A European Union mandate from 2012 requires IMB of *energy* consumption in newly constructed homes – but only if the implementation is economically feasible. For *water* consumption, the European Union adopted the Water Framework Directive in 2000 with one of the policy objectives being "getting the prices right".

IMB is attractive because it could fulfill all five criteria for effective governance of commons as identified by Dietz, Ostrom, and Stern (2003).[1]

We have collected apartment-level data from a housing company in the municipality of Kumla in Sweden. The panel data cover daily consumption for the years 2011–2017, and IMB was introduced between 2012 and 2016 at different dates across the apartments. The data is close to ideal for applying a quasi-experimental design for studying the effects of switching from a zero to a marginal cost reflecting the markert price on consumption.

We find that IMB reduced hot water consumption by 26%. The reduction was driven predominantly (72%) by heavy users in the top consumption quartile. Our results imply that there is a severe common pool problem in water consumption and that introducing a marginal cost can curb free-riding behavior. Like in experimental laboratory settings (e.g., Fehr and Fischbacher, 2003), a minority of free-riders can have a large impact. Moreover, our calculations suggest that IMB of hot water is a cost-effective policy tool.

Our paper adds to the growing literature using quasi-experiments or experiments to study the effects of policy interventions on resource and energy management (e.g., Allcott, 2011; Jessoe and Rapson, 2014; Elinder et al., 2017; Ito et al., 2018; Jack and Smith, 2020; Jessoe et al., 2021; Ornaghi and Tonin, 2021). In the case of water conservation, inspired by the broader literature in behavioral economics on the role of salience (e.g., Duflo and Saez, 2003; Chetty et al., 2009; Fadlon and Nielsen, 2019), the focus has been on the effects of providing consumers with various types of information. Daminato et al. (2021) found that access to real-time data on consumption levels reduces household water use by 2%. In contrast, Wichman (2017) and Brent and Ward (2019) found that providing more information on water use and price plans *raises* consumption in many cases. Such results might be rationalized by consumers realizing that water is cheap, or because paying a price could alleviate the moral guilt of overconsumption (Gneezy and Rustichini, 2000). Along similar lines, Wang (2018) found that many consumers are rationally inattentive to the water bill since it only accounts for a small fraction of household expenditures. This result raised doubts on whether small monetary incentives have any impact on water consumption.

A couple of papers have investigated the effects of non-pecuniary incentives on water consumption. Ferraro et al. (2011) showed that providing a water report including social comparisons reduces water use by up to 4.8% in the short run, and 1.3% two years later, which is much more effective than merely appealing to pro-social preferences. Similarly, Brent et al. (2015) and Torres and Carlsson (2018) found effects up to 5% and 6.8%, respectively.[2]

In comparison with the effects of providing information or non-pecuniary incentives, the 26% IMB effect we find of changing price scheme, from a zero marginal cost to one that corresponds to the market price, is of an order of magnitude higher.[3] Moreover, our IMB effect

[1] The criteria are: (i) resources can be easily monitored, (ii) the local economic and social circumstances are rather stable, (iii) there are functioning social networks within the community, (iv) outsiders can be excluded from the resource pool, and (v) the strategy is supported by the resource users.

[2] In a non-experimental setting, Bollinger et al. (2020) identified peer effects in residential water consumption during dry and hot summers.

[3] Whereas the cited papers isolate information and non-pecuniary effects holding pricing constant, we isolate the effect of pricing holding information and non-pecuniary effects constant. The IMB process started with the introduction of a meter monitoring household consumption and data became available for the households and for us. Within two years, individual billing starts, and our IMB effect applies only to the change in price plan.

appears to be permanent, and the IMB system is automatic with a low maintenance cost once introduced. Among policy instruments (Stavins, 2011), our results suggest that price incentives have very attractive features for promoting resource conservation, even for cheap resources.

There are two recent papers that are closely related to ours. Elinder et al. (2017) study the effect of IMB on electric energy consumption in multi-family buildings in Sweden, and Ornaghi and Tonin (2021) study the IMB effect on total household consumption of water using data from predominantly single-family houses in southeast England. Both studies find large reductions in consumption (25% and 22%, respectively), and that the free-riding effect is concentrated to a small group of households. Our study combines the water and energy dimensions as we focus on *hot* water consumption in multi-family houses. We also differ from Ornaghi and Tonin (2021) in that our estimates are not influenced by outdoor water use such as garden irrigation, and thus our paper relates more to resource management in cities.

Our paper also contributes to the long-standing literature on how water consumption responds to price changes (e.g., Hewitt and Hanemann, 1995; Dalhuisen, 2003; Klaiber et al., 2014; Olmstead et al., 2007; Wolak, 2016). Whereas we investigate the extensive margin effect of introducing a marginal cost, this literature is interested in intensive margin effects of different positive marginal costs. Reported elasticity estimates vary substantially between 0 and 0.75. However, there is concern about whether the estimates reflect causal demand effects. Olmstead and Stavins (2009) summarized the early literature and concluded that price incentives appear more cost effective for managing water demand than non-pecuniary conservation programs. Recently, Browne et al. (2021) exploited price hikes due to policies enacted during drought periods in California and they found an elasticity of 0.16. To achieve a 26% consumption reduction (as we find following IMB introduction) would require more than doubling the price, indicating that our extensive margin responses are strong compared to intensive margin responses.

The paper proceeds as follows. The next section introduces the institutional background. We describe the IMB intervention in Section 3 and our data in Section 4. Section 5 outlines the empirical strategy. Estimation results are reported in Sections 6 to 8, and cost-benefit calculations are provided in Section 9. The last section concludes.

2. Institutional background

Residential water consumption comprises 23% of total fresh water use in Sweden (Statistics Sweden, 2017), and consumption of hot water makes up a third of this share (Swedish Energy Agency, 2012). Hot water use accounts for 15% of residential energy use. In multi-family buildings in which about half the Swedish population reside, district heating is the main energy source for the production of hot water and heating, and this accounts for nearly 7% of total energy use in Sweden (Swedish National Board of Housing, Building and Planning, 2008).

Since the 1970s, the Swedish Energy Agency has proposed that households should use IMB for electricity and hot water consumption. However, IMB only became popular later on as a result of technological advances making its implementation cheaper. Still today only 15–

20% of all apartments have IMB of hot or cold water.[4] Moreover, big construction companies as well as the Swedish National Board of Housing, Building and Planning (2008, 2015, 2018) have repeatedly claimed that IMB is not a cost-efficient policy. It is therefore not surprising that a majority of multi-family buildings still lack IMB.

At the European Union level, Article 9 of European Union Energy Efficiency Directive from 2012 requires IMB of energy consumption, including hot water, in newly constructed or renovated multi-family buildings — but only if the implementation is economically feasible. In 2014, the European Union also committed to install 200 million units for electricity and 45 million units for gas by 2020 (European Commission, 2014). Following these efforts to achieve energy efficiency, the Swedish government decided in 2019 that all multi-family buildings should have IMB of both electricity and hot water consumption at the latest by July 1, 2021 (Swedish National Board of Housing, Building and Planning, 2020). However, this target has not been achieved.

3. The IMB intervention

We investigate the introduction of apartment-level IMB by Kumlabostäder in its multi-family buildings. Kumlabostäder is the municipal public enterprise in charge of publicly provided rental units in the municipality of Kumla in Sweden.[5] Infometric is the company that installed and monitors IMB systems for Kumlabostäder. While the goal was to introduce IMB in every apartment, IMB was introduced at different dates between 2012 and 2016 across different apartments in Kumlabostäder's housing stock. The discrepancy in dates arises because the installation of meters took some time, but also because the tenants in each building were involved in deciding exactly when to begin the installation and billing process.

In most cases, there was a time gap of over a year between the installation date, after which consumption was monitored, and the actual apartment-level billing began. This allows us to measure consumption before and after the individual billing, which we refer to as the IMB treatment. Since consumption data was available not only for us but also for the households already in the pre-treatment period (between installation and billing dates), our billing effect is not confounded by effects due to changes in the availability of consumption information.[6]

Before the treatment, all tenants in Kumlabostäder's housing stock implicitly split the total bill for cold and hot water, since the landlord, who formally pays the bill, passes on the costs to the tenants' rents in proportion to their apartment size. With many apartments dividing the bill, each apartment could use water at an almost fixed cost independent of household consumption, and hence at an approximately zero marginal cost on both hot and cold water. After the treatment, IMB monitored *hot* water use in each apartment. Both tenants and the landlord could see the use in real time through a web application. The households had to pay an amount (separately specified on their monthly rental bill) proportional to their hot water consumption with a price of approximately 90 SEK per 1,000 liters (2018 price level when 1

[4] This estimate comes from one of the leading companies supplying IMB solutions in Sweden, Infometrics AB.
[5] Kumla is a mid-sized town located in between Stockholm and Gothenburg.
[6] Many households do not check consumption data even when available. It is, of course, possible that households became more aware of their levels of consumption only after they received the first individual bill. We cannot distinguish the effect of this awareness from the effect of the price change.

USD was worth 8.7 SEK). IMB introduced only a marginal cost on use of hot water, and not on use of cold water. However, the price covered Kumlabostäder's actual acquisition cost of not only the hot water but also the average amount of cold water used per liter of hot water consumption in their housing stock.[7]

Hot water is produced at the building-level by heating cold water using a certain energy source, typically district heating. Because of the energy cost for heating the water, the per liter price of hot water is nearly three times the price of cold water. Households typically use a mix of hot and cold water when using a water tap. While free-riding behavior was still possible for cold-water consumption after IMB and most of the cost for hot water reflected energy cost, IMB was likely perceived to have introduced incentives to save water in general. The monthly water bill was approximately 260 SEK per month and apartment before IMB introduction (30 USD at the 2018 price level).

4. Data and descriptive statistics

We have panel data with daily observations of total hot water consumption at the apartment level over seven years. For some apartments, we can also differentiate between bathroom and kitchen use of hot water. There are some obvious mis-recorded entries in the data. We replace the value of daily consumption with a missing value if the entry is negative or larger than 10,000 liters, which corresponds to having about one water tap on all day long. Daily use is typically highly fluctuating over time, and we use monthly means of daily use (liters per day) for each apartment in our analysis.

We divide the apartments in our sample into four groups depending on their IMB treatment dates, keeping only apartments for which we observe water use for at least three months before the introduction. In Table 1, we report for each group the IMB introduction date as well as numbers of apartments and buildings, months of available data, and apartment-month level observations. Our analysis sample consists of 613 apartments in 33 multi-family buildings from January 2011 to December 2017. In total, we have 44,591 observations. Most apartments in our sample belong to group 2 with the treatment date July 1, 2012.

Table 1. IMB introduction dates and number of observations

	Group 1	Group 2	Group 3	Group 4	Total
IMB date	April 1, 2012	July 1, 2012	May, 1 2013	Dec 1, 2016	
Apartments	30	396	139	48	613
Buildings	1	20	9	3	33
Months	79	83	59	24	245
Observations	2,370	32,868	8,201	1,152	44,591

We match the water consumption data from Infometric with data on apartment characteristics, including size, number of rooms, and yearly rent, obtained from Kumlabostäder. Table 2 reports means of observable characteristics by treatment group and shows that there is some variation in apartment characteristics across the groups. On average, apartments in group

[7] Thus, only households using an average mix of hot and cold water paid the exact market price of the mix.

2 (with the largest number of apartments) are a bit smaller (with respect to size and rooms) and also have lower rent. However, total water use is higher than in the other groups.

Table 2. Variable means by groups during the sample period

	Group 1	Group 2	Group 3	Group 4	Total
Total water use (l/day)	59.99	76.83	75.82	58.55	75.28
Bathroom use (l/day)	35.05	45.12	n/a	n/a	44.14
Kitchen use (l/day)	24.94	31.32	n/a	n/a	32.06
Temperature (°C)	22.30	22.40	22.58	23.06	22.45
Size (m^2)	64.45	61.44	77.60	60.65	64.35
Rooms	2.60	2.17	2.69	2.17	2.28
Rent (SEK/year)	62,550	54,760	81,970	85,446	60,659

In Figure 1, we plot total across-apartment means of hot water use over time. Dashed lines mark the first month of billing following the IMB introduction dates at which apartments switch treatment status (see Table 1). The figure shows that there are strong seasonal patterns with higher consumption during winter months compared to summer months.

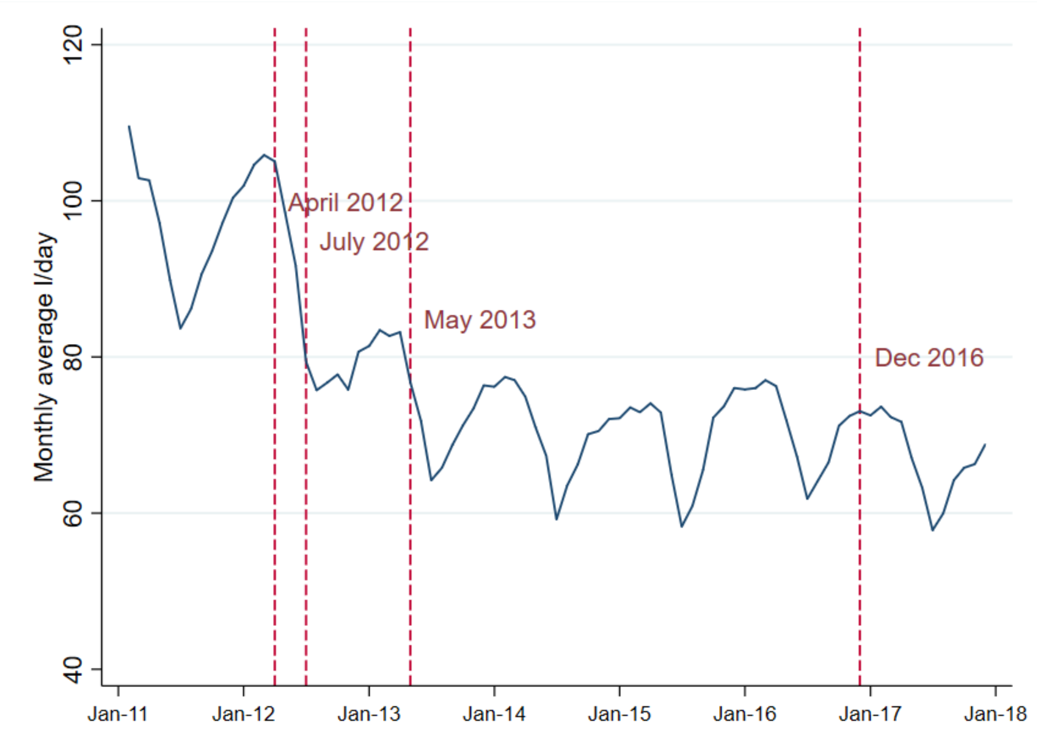

Figure 1. Monthly means of daily hot water use over time

Note: Dashed lines mark the first month following the IMB introduction dates in the four groups

In Figure 2, we plot hot water use over time for each of our four groups. There are visible sharp drops at the treatment months. Most of our apartments belong to group 2. Comparing the same calendar month before and after the treatment, we see that peak consumption levels are around 110 liters per day before the treatment and 80 liters per day thereafter. The other groups have fewer apartments and observations from a shorter pre-treatment period. While the overall pattern does not contradict the one found for group 2, there is considerable noise.

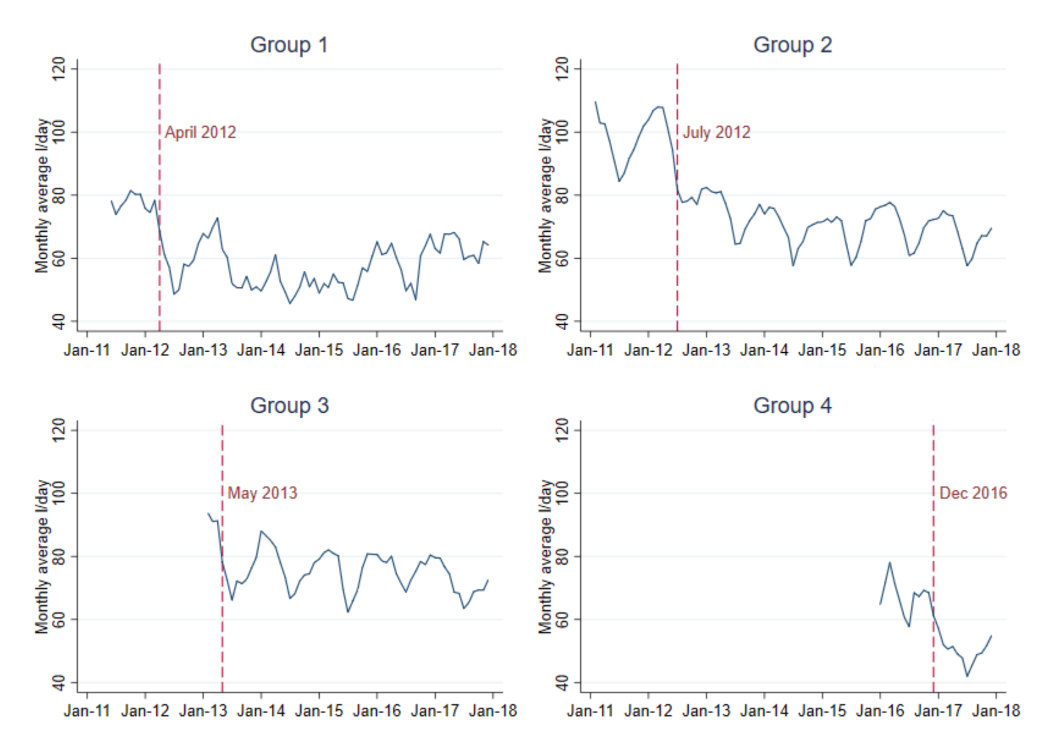

Figure 2. Monthly means of daily hot water use by groups over time

Note: Dashed lines mark the first month following the IMB introduction dates in the four groups

In addition to hot water use, Infometric also records daily average temperature in the apartments. Since heating is not part of the hot water bill, our IMB introduction should not affect temperature.[8] We can thus use the temperature variable (monthly means of the daily averages) to verify that following the IMB treatment for hot water use, there is no treatment effect on temperature. In Figure A1 in the Appendix, we report graphs corresponding to Figure 2 for temperature showing that the IMB treatment did not have a visual impact on this variable.

5. Empirical strategy

We estimate the IMB effect following the introduction of individual billing using within-apartment variation in hot water use over time. To enable a proportional interpretation of effects, as the dependent variable, we use the logarithm of hot water use $ln\,Water_{it}$ varying by apartment i and date t.[9] For estimation purposes, a date is a combination of calendar month and year, and dates are spaced one month apart. An IMB treatment dummy T_{it} is set to zero for apartments without IMB and switched to one after IMB introduction. We rely on within-apartment variation by accounting for time-invariant apartment fixed effects μ_i absorbing differences across apartments that remain constant over time. We account for time effects using a vector of time-varying month dummies in $\boldsymbol{M}_t$.

[8] In most Swedish multi-family buildings, heating is provided centrally in a split-the-bill fashion (Swedish National Board of Housing, Building and Planning, 2015).

[9] We use the logarithm of consumption plus a constant equal to one to avoid that the logarithm of zero is not defined. While we use one as the constant, the results are not sensitive to using a larger (but still small) number.

We estimate the following regression equation by ordinary least squares:

$$ln\,Water_{it} = \alpha + \beta T_{it} + \boldsymbol{\gamma} \boldsymbol{M}_t + \mu_i + \varepsilon_{it}. \quad (1)$$

The parameter β captures the IMB effect, α is an intercept, and ε_{it} is an idiosyncratic error term. We cluster standard errors at the apartment level. When reporting the treatment effect, we report $(e^{\beta} - 1) * 100$, which is the percentage effect of IMB introduction on water use.

We employ two different specifications with different time-varying controls: First, we let $\boldsymbol{M}_t$ be a vector of *calendar month* dummies. This should capture the seasonal effects we saw in Figures 1 and 2. In this specification, identification requires that there are no remaining time effects correlated with treatment status. This means that in the counterfactual case absent IMB introduction in an apartment, consumption should not systematically differ before and after the treatment date, which rules out the existence of trends in consumption over time.

Second, we let $\boldsymbol{M}_t$ be a full set of date dummies (which correspond to including date fixed effects). This specification is a differences-in-differences specification that controls for any potential time-varying confounding factors, including seasonal effects and time trends. Identification is possible because of the staggered IMB introduction across groups. The difference-in-differences method compares apartments that switch treatment status at a certain date (treatment group) with other apartments without treatment status change at that date (control group).[10] The identifying assumption is that the two groups have parallel trends in the counterfactual case (without any apartments switching treatment status).

To allow and test for placebo, anticipation, and dynamic post-treatment effects following IMB introduction, we complement the specification in Eq. (1) with an event-study specification:

$$ln\,Water_{it} = \alpha + \sum_{n \leq -4} \beta_n T_{n,it} + \sum_{n=-2,-1} \beta_n T_{n,it} + \sum_{n \geq 0} \beta_n T_{n,it} + \boldsymbol{\gamma} \boldsymbol{M}_t + \mu_i + \varepsilon_{it}, \quad (2)$$

The event-time index n is defined such that $n = 0$ in the month following IMB introduction, $n = 1$ the month thereafter, and so forth. Similarly, a negative n is used for a date before IMB introduction. A dummy variable $T_{n,it}$ takes a value of one at event-date n and zero otherwise. Thus, $T_{0,it} = 1$ at date t in the month following IMB introduction for apartment i. We let the third month before IMB treatment be the omitted base date.[11] Thus, we allow two months of estimated anticipation effects given by β_n where $n = -2$ or $n = -1$. Dynamic effects following IMB introduction are given by β_n for $n \geq 0$. We report the different β_ns for this specification. Event-dates with $n \leq -4$ serve as pre-treatment periods without anticipation effects. To reasonably argue that β_n identify causal effects for $n \geq -2$, there should not be an effect in periods $n \leq -4$. Thus, many insignificant or small placebo estimates of β_n for $n \leq -4$ relative to for $n \geq -2$ would constitute empirical evidence in favor of the identifying assumption.

[10] Thus, potential consumption change due to time effects unrelated to IMB for the apartments that switch treatment status is approximated by the consumption change for the apartments that do not change treatment status. In our case, every apartment will serve as treatment group at some date and control group at other dates.

[11] Thus, IMB effects apply relative to the pre-IMB consumption level in the third month before IMB introduction. This contrasts the specification in Eq. (1) where every pre-IMB date serve as base dates. If there were no pre-IMB effects and no (or small) anticipation effects, this difference in base dates between the specifications in Eq. (1) and (2) would not drive a potential discrepancy in estimated IMB effects.

6. Main estimates

In Table 3, we report our panel estimates of the IMB effect on hot water use, estimated using Eq. (1). We report estimates with and without calendar month dummies, date fixed effects, or apartment fixed effects. The estimated IMB effect on consumption reduction is about 26% in columns (1) to (4), which corresponds to an average reduction in water bill of 66 SEK (7.6 USD at the 2018 price level) per month. The point estimates are statistically significant at the 1% level. We can also interpret the effect using the consumption level *with* IMB as the base, and in this case, consumption is estimated to be 34% higher *without* IMB. Hence, the results indicate that there is a serious common pool problem when there is no marginal cost of consumption (without IMB).

Table 3. Estimates of the IMB effect for the full sample

	(1)	(2)	(3)	(4)	(5)
IMB effect (%)	-27.16**	-25.84**	-26.87**	-25.51**	-16.45**
	(2.543)	(2.624)	(2.412)	(2.487)	(3.969)
Calendar month dummies	No	Yes	No	Yes	No
Date fixed effects	No	No	No	No	Yes
Apartment fixed effects	No	No	Yes	Yes	Yes

Notes: Log water use is the dependent variable and IMB treatment is the main independent variable. Eq. (1) provides the regression equation. We report $e^{\beta} - 1$ which is the percentage effect of IMB on water use, and standard errors accounting for the same transformation are clustered at the apartment level in parentheses. * p<0.05, ** p<0.01.

When including date fixed effects instead of calendar month dummies in column (5), standard errors rise substantially and the point estimate drops by a third (from -25.51 to -16.45). The unbalanced nature of our panel data and the staggered IMB introduction are the reasons for the loss of precision. The difference-in-differences specification used in column (5) compares apartments that at a certain date switch treatment status with other apartments without such a switch at that date. However, as IMB is introduced in group 1, there are only observations from group 2 serving as the control group (see Figure 2), and vice versa when IMB is introduced in group 2. The problem is magnified by most apartments belonging to group 2, meaning that there is only a small control group (group 1) when group 2 switches treatment status. Moreover, the overlap in time where groups 1 and 2 have different treatment status is small (April 2012 to July 2012) implying that few observations contribute to the identification of the IMB effect. Thus, relaxing the identifying assumption of column (4), using the specification in column (5), comes with a drawback in terms of deterioration of precision. Nevertheless, the two point estimates in columns (4) and (5) are not statistically different from each other.

Our event-study specification in Eq. (2) allows us to estimate anticipation and dynamic post-treatment effects and to assess the identifying assumptions in the two different panel specifications with calendar month dummies and date fixed effects, respectively. We plot estimates of placebo, anticipation, and dynamic post-treatment effects in Figures 3 and 4 below. For clarity, we limit the presentation of dynamic post-treatment effect estimates to a post-IMB period that is equally long as the pre-IMB period. Base date is set to the third month before IMB introduction, and we have added two vertical dashed lines to mark the anticipation period.

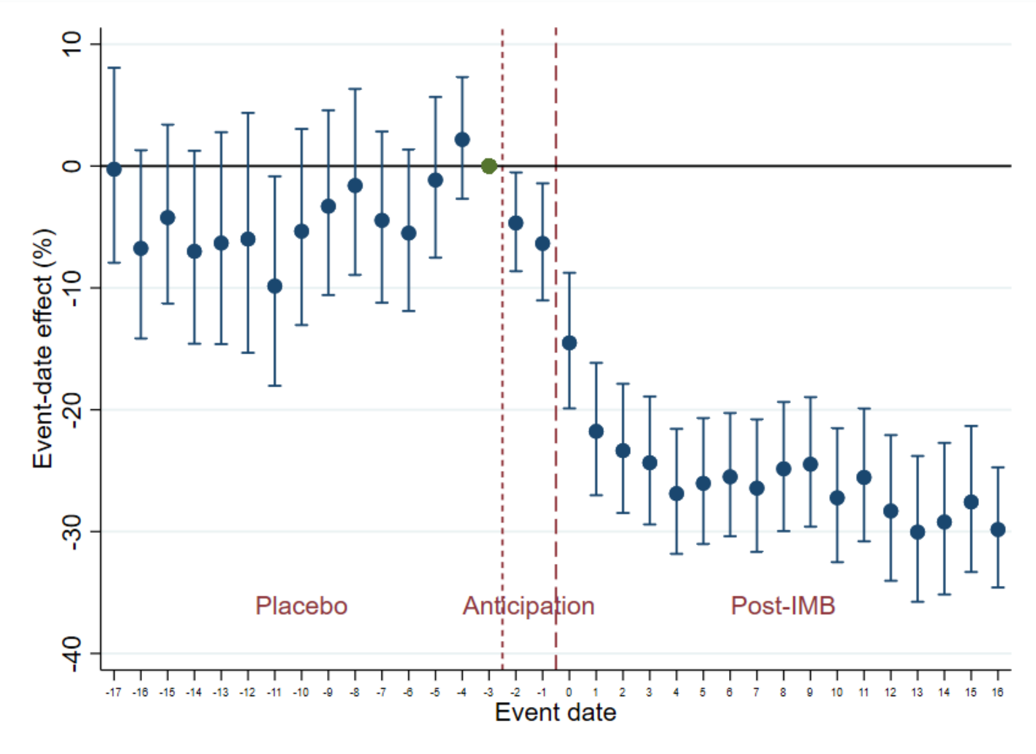

Figure 3. Event-study estimates from the specification with calendar month dummies

Note: Eq. (2) is the regression equation. Event date 0 refers to the first post-IMB date, and event date -3 is the base date. We report $e^{\beta} - 1$ using points and correspondingly transformed 95% confidence intervals using bars.

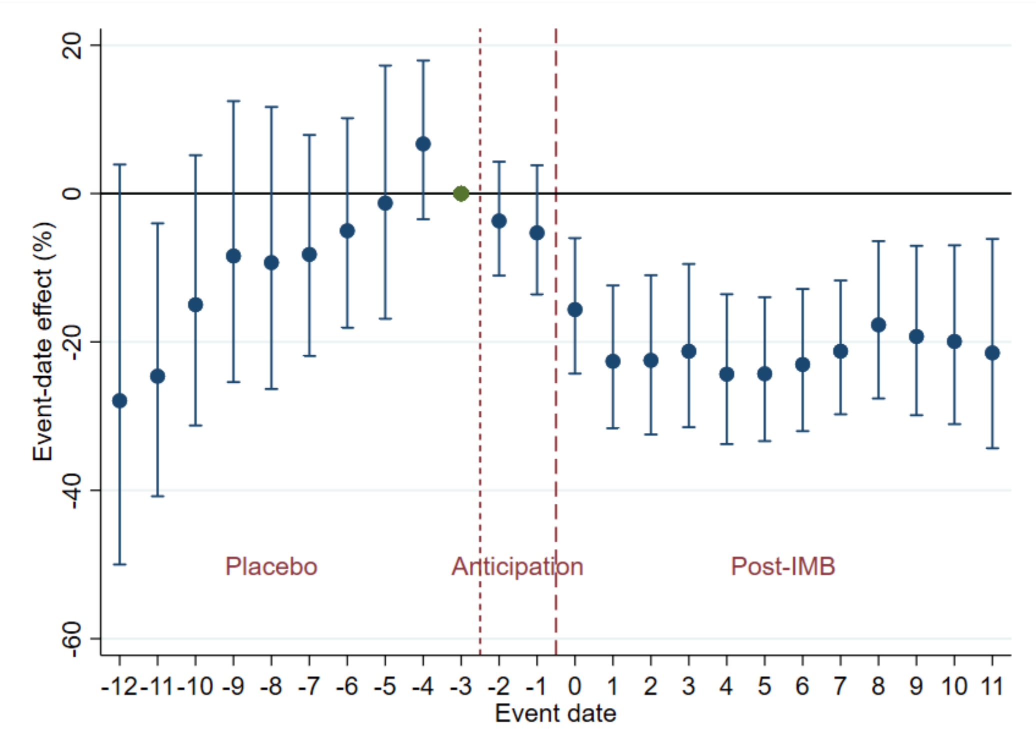

Figure 4. Event-study estimates from the specification with date fixed effects

Note: Eq. (2) is the regression equation. Event date 0 refers to the first post-IMB date, and event date -3 is the base date. We report $e^{\beta} - 1$ using points and correspondingly transformed 95% confidence intervals using bars.

Figure 3 shows that point estimates are small in the pre-IMB period compared to the point estimates in the post-IMB period. Out of 14 placebo point estimates for event dates before -3, only one is statistically significant at the 5% level. Given the large number of placebo tests, one would expect an occasional statistically significant estimate even if there were no placebo effects. Moreover, there is no systematic pattern in placebo estimates over event dates (e.g., no increasing trend over event dates) suggesting that the discrepancies from a zero point estimate are due to random noise. Thus, the placebo estimates strongly support the validity of our identifying assumption for the specification with calendar month dummies.

Figure 4 reveals a similar pattern as the one in Figure 3. However, placebo point estimates in Figure 4 could be quite large, and the point estimates for event dates before -9 are similar in magnitude to the post-IMB point estimates but much less precise. The reason is that there are few pre-IMB observations for these event dates and this fact not only inflates standard errors but also increases the variability of point estimates. Overall, despite requiring a weaker identifying assumption with date fixed effects, we find the specification with calendar month dummies preferable, not only because of higher precision but also because there is more reliable empirical support for the identifying assumption it relies on. However, the overall conclusion is similar in the two specifications, and our results are robust to assuming the weaker identifying assumption.

In Figure 3, we also find that potential anticipation effects are small. Estimated effects are statistically significant at the 5% level, but the point estimates are small relative to post-IMB point estimates and of similar magnitude as the placebo point estimates. Moving to estimates of dynamic effects following IMB introduction, we find that the IMB effect kicks in quite immediately, and the estimated effect reaches its full long-run strength in the second post-IMB month (at an event date of 1). After that, the estimated consumption reduction is remarkably stable around 26% confirming the main estimated effect in column (4) of Table 3.

In Table A1 of Appendix, as another type of placebo test, we report estimates corresponding to the ones in Table 1, but for the effect of IMB on temperature. The point estimates are small across the specifications and not statistically significant at the 5% level in the specification with calendar month dummies in column (4). This is reassuring since IMB of hot water use does not affect heating costs.[12]

7. Subgroup estimates

In Table 4, we report estimates from our preferred specification in Eq. (1) with calendar month dummies for each group of apartments with different IMB introduction dates. For groups 1 and 2, we also have water use separated between bathroom and kitchen use and report estimated IMB effects for these subcategories of water consumption. We find IMB effects between about 20 and 30%, and quite similar for bathroom and kitchen use. Given somewhat different characteristics of apartments in the different groups, and fewer observations in groups 1, 3, and 4 compared to group 2, some differences in point estimates between groups are expected. None

[12] In the specification with date fixed effects in column (5) of Table A1, the point estimate is small (IMB effect of -0.2 degree Celsius) but statistically significant, underscoring that the specification with calendar month dummies is more trustworthy.

of the estimated effects is statistically different from each other. The similarity of estimated effects across groups with different treatment dates also alleviates the potential concern that for random reasons, something else happened at the treatment date of a particular group causing the following consumption reduction.

Table 4. Estimates of IMB effects by groups with different IMB dates

	(1) Group 1	(2) Group 2	(3) Group 3	(4) Group 4
Total IMB effect (%)	-29.08**	-26.08**	-19.05**	-19.66*
	(6.787)	(2.852)	(4.451)	(7.001)
Bathroom IMB effect (%)	-24.42*	-24.65**		
	(7.870)	(3.482)		
Kitchen IMB effect (%)	-35.54**	-28.98**		
	(6.271)	(3.348)		
Calendar month dummies	Yes	Yes	Yes	Yes
Apartment fixed effects	Yes	Yes	Yes	Yes
Observations	2,370	32,868	8,201	1,152

Notes: Log water use is the dependent variable and IMB treatment is the main independent variable. Eq. (1) provides the regression equation. We report $e^{\beta} - 1$ which is the percentage effect of IMB on water use, and standard errors accounting for the same transformation are clustered at the apartment level in parentheses. * p<0.05, ** p<0.01.

In Table 5, we report IMB effects by apartment size, number of rooms, and rent. Estimated effects vary between 23% and 30% and are all statistically significant. Hence, we find little evidence of heterogeneous effects across apartments with different characteristics.

Table 5. Estimates of IMB effects by groups with different apartment characteristics

	(1)	(2)	(3)
		A. Size	
	<= 55 m	55–72 m	> =72 m
IMB effect (%)	-25.88**	-23.14**	-29.07**
	(5.823)	(3.659)	(3.970)
		B. Rooms	
	1	2	>=3
IMB effect (%)	-28.07**	-23.25**	-27.17**
	(6.855)	(3.798)	(3.510)
		C. Rent	
	<= 48,000 SEK	48,000–61,000 SEK	>=61,000 SEK
IMB effect (%)	-25.27**	-24.92**	-26.42**
	(5.622)	(4.291)	(3.414)
Calendar month dummies	Yes	Yes	Yes
Apartment fixed effects	Yes	Yes	Yes

Notes: Log water use is the dependent variable and IMB treatment is the main independent variable. Eq. (1) provides the regression equation. We report $e^{\beta} - 1$ which is the percentage effect of IMB on water use, and standard errors accounting for the same transformation are clustered at the apartment level in parentheses. * p<0.05, ** p<0.01.

8. Results by consumption quartiles

Free-riding behavior may vary depending on the needs of a household. To explore such heterogeneous IMB effects, for the largest group of apartments in group 2, we divide the apartments into four quartiles depending on the levels of per square meter hot water use. In determining quartile cutoffs, we calculate for each apartment its pre-IMB average (across-date average in the pre-treatment period) and its post-IMB average. We then take the mean of the pre- and post-treatment averages. The four quartile groups are based on the distribution of this mean.[13] Hence, we account for both pre- and post-IMB levels when determining whether an apartment (on average) had heavy users.

We could, alternatively, have defined quartile cutoffs based only on either pre- or post-IMB levels. However, using our definition avoids mean reversion issues due to apartments changing tenants over time somewhat randomly. To illustrate how mean reversion occurs, assume that a heavy user resides in an apartment. If the next tenant is a random draw, that tenant is more likely to use less water. For this reason, apartments with heavy users in the pre-IMB period are likely to have fewer heavy users as time passes in the post-IMB period.[14] Mean reversion would lead to a decreasing time trend that confounds the IMB effect. To demonstrate that our method circumvents the issue with mean reversion unlike the alternative methods with other quartile definitions, we have included some placebo exercises in Appendix B. Appendix B shows that our method delivers insignificant placebo point estimates during placebo periods without IMB switch, unlike the alternative methods.

In Figure 5, we plot the development of consumption over time separately for each consumption quartile for group 2. Both the absolute and proportional effects appear the greatest for the top quartile of heavy water users.

In Table 6, we report estimated IMB effects by apartments in different consumption quartiles for group 2. We find estimated effects of about 23% and 24% for quartiles 1 and 3 (columns 1 and 3), which are close to the estimated effect of 26% for the pooled sample with all quartiles (in column 4 of Table 3). The effect for quartile 2 is lower and not statistically significant. The main result of Table 6 is, however, that the estimated effect is much greater for the top quartile where IMB decreased consumption by 43% (column 4).

Since pre-IMB water use varies across consumption quartiles, the same percentage effect translates into different absolute (level) effects. In Table 7, we also report how the percentage IMB effects translate into absolute effects. From these absolute effects, we can calculate the percentage contribution of each quartile to the total effect (sum of absolute effects) across quartiles. We see that the absolute effect in quartile 4 is at least four times larger than in the other groups. Quartile 4 contributes to 72% of the total IMB effect across the quartiles. Heavy users may have a higher baseline water need. Nevertheless, the fact that small price incentives have great effects indicates wasteful behavior in the absence of IMB. The common pool problem can be severe even when the group of free-riders is small.

[13] If pre- and post-IMB periods were equally long, the mean of the pre- and post-IMB averages would just be the mean across all dates.

[14] A similar reasoning applies to apartments with heavy user in the post-treatment period: Those apartments were likely to have had fewer heavy users in the pre-IMB period.

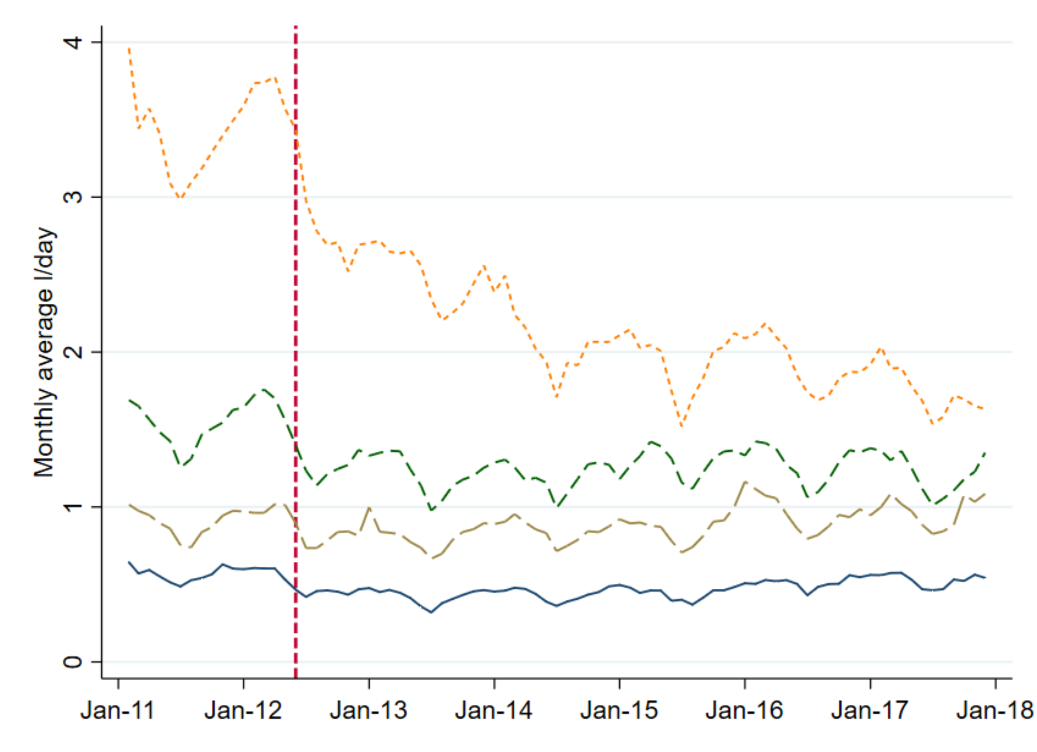

Figure 5. Monthly means of hot water use by consumption quartiles for group 2 over time

Note: A dashed line marks the first month following the IMB introduction. We divide the apartments into four quartiles based on consumption means of pre- and post-IMB averages.

Table 6. Estimates of IMB effects by consumption quartiles for group 2

	(1) Quartile 1	(2) Quartile 2	(3) Quartile 3	(4) Quartile 4
IMB effect (%)	-22.77**	-10.01	-24.44**	-43.08**
	(5.772)	(7.559)	(5.028)	(4.286)
Calendar month dummies	Yes	Yes	Yes	Yes
Apartment fixed effects	Yes	Yes	Yes	Yes
Pre-treatment average	38.40	56.95	100.75	228.21
Absolute effect	-8.74	-5.70	-24.62	-98.31
% of total abs. effect	6.37	4.15	17.92	71.56

Notes: Log water use is the dependent variable and IMB treatment is the main independent variable. Eq. (1) provides the regression equation. We report $e^{\beta} - 1$ which is the percentage effect of IMB on water use, and standard errors accounting for the same transformation are clustered at the apartment level in parentheses. The apartments are divided into four quartiles based on consumption means of pre- and post-treatment averages. The pre-treatment averages reported are adjusted for calendar month effects. * p<0.05, ** p<0.01.

9. Cost-benefit calculations

The Swedish National Board of Housing, Building and Planning (2008, 2015, 2018) among others has questioned whether IMB for hot water is cost effective. Using our estimated IMB effect, we compare IMB investment costs with three monetary measures of social benefits: (i) the efficiency gain associated with removing overconsumption due to free-riding, (ii) the cost that would have been required to conserve a similar amount of water by buying it from the market and let it remain in nature, and (iii) the social value of reducing CO_2 emissions related to hot water production.

Infometric has provided us with average costs of installing IMB for hot water. The installation cost of a meter is approximately 2,000 SEK with an annual maintenance cost of 80 SEK. Every 15 years, larger updates of meters and software are required at a cost of 1,500 SEK. With an interest rate of 5%, IMB comes at an annualized cost of 250 SEK.[15]

Our estimated 26% IMB-effect (in column 4 of Table 3) corresponds to a hot water reduction of 24.61 liters per day and 8,982 liters per year in each apartment. In Figure 5, we plot the resulting demand curve under the assumption that it is linear. If the market price (0.09 SEK per liter) reflects the social marginal costs of hot water production, the figure also shows the deadweight loss (DWL) associated with overconsumption of hot water when the marginal cost of consumption is zero without IMB.[16] IMB reduces the annual water cost by 808 SEK (=C+DWL=8,982×0.09) per tenant, and the efficiency gain of eliminating the deadweight loss is thus 404 SEK per apartment and year.

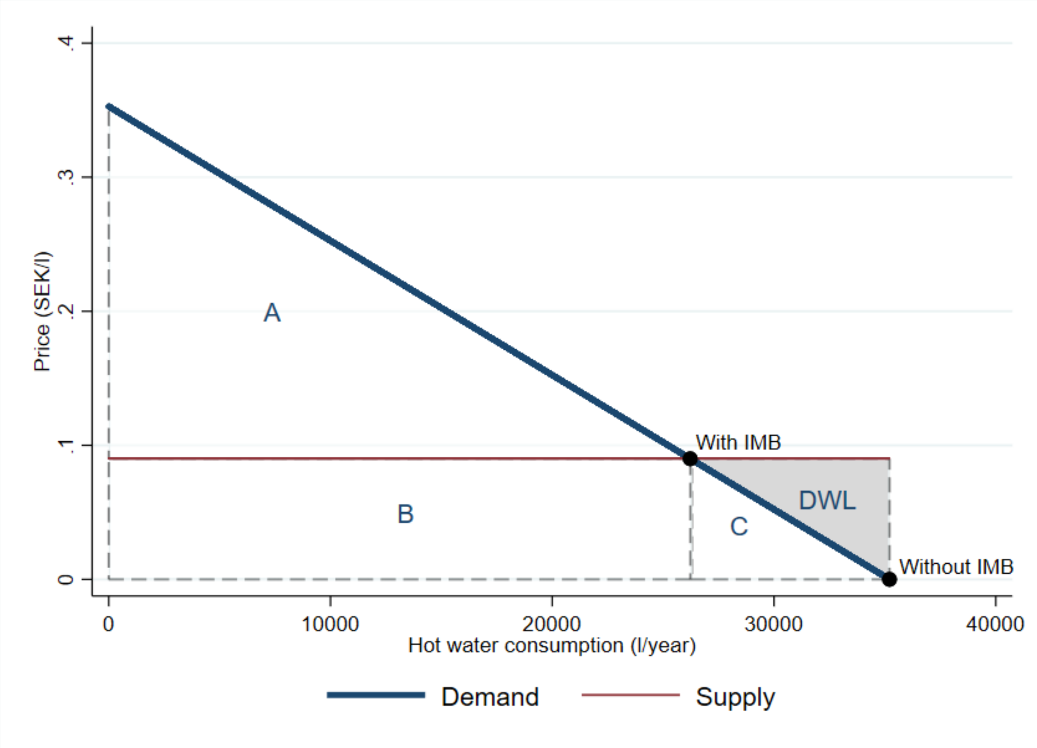

Figure 5. Deadweight loss without IMB

Our surplus calculations for IMB suggest that the efficiency gain exceeds the costs by more than 60% (DWL=404 SEK vs. costs of 250 SEK per year). In other contexts, where the

[15] The present value of meter installation and update costs is $2000 + \sum_{i=1}^{\infty}(1500/1.05^{15i}) = 2000 + 1500/(1.05^{15} - 1)$. Let AUC be the annualized user cost of the meter from one year after the meter installation (when IMB starts). Then, the present value of the stream of annualized costs is $\sum_{j=1}^{\infty}(AUC/1.05^{j}) = AUC * 0.05$. Equating the two present values gives $AUC \approx 170$. Adding the annual maintenance cost of 80 gives the annualized IMB cost of 250.

[16] The producer surplus is zero, and the consumer surplus is A-DWL (=A+B+C-B-C-DWL) without IMB and A with IMB. Thus, the efficiency gain with IMB is the deadweight loss DWL.

costs for cold water or heating are lower, demand is less elastic, or IMB costs are higher, the net benefit is lower and could in some cases be negative. However, in the current setting, the benefits exceed the costs by a wide margin. Two factors, however, point to even larger net benefits in many contexts. First, IMB costs are likely to continue to fall in the future and they are also lower when IMB is installed in new buildings. Second, in many locations water is from time to time limited in supply, with very high alternative costs, causing the deadweight loss from overconsumption to be potentially much higher.

How cost effective is IMB as a water conservation tool? IMB saves 8,982 liters of hot water at a cost of 250 SEK per year, i.e., 36 liters per SEK. Given that hot water comprises a third of total household water consumption (including cold water), a total of 108 liters of water are saved per invested SEK. In comparison, suppose that the government wants to conserve water by buying it on the market and let it remain in nature, e.g., during a drought. At the current market price (24 SEK/1,000 liters in Kumla in 2021), the government can spend 1 SEK to buy 42 liters of cold water, i.e., less than half the amount of (108 liters of) water that a 1 SEK investment in IMB saves.

What is the potential for IMB in reducing CO_2 emissions? Heating 36 liters of cold water into hot water requires 1.98 kWh energy (0.055 kWh per liter according to the Swedish Energy Agency, 2012). Globally, producing 1 kWh of electric energy generates on average 0.475 kg CO_2 (International Energy Agency, 2019). Carleton and Greenstone (2021) estimate that the social cost of carbon is 125 USD per ton of CO_2 emissions (1.09 SEK/kg).[17] Thus, a 1 SEK investment in IMB reduces CO_2 emissions by 0.940 kg (=1.98×0.475) with a social value of 1.02 SEK (=0.940×1.09). Of course, energy-related emissions vary substantially between countries. Moreover, while estimates of the social cost of carbon have increased over time and many increase further, the range of existing estimates is wide. Nevertheless, our calculation suggests that in many countries today, the social value of the reduced emissions of CO_2 in itself motivates the IMB investment costs.[18]

10. Conclusion

Water is becoming an increasingly scarce resource around the world. Yet, it is often distributed such that consumers face too low marginal costs, creating a common pool problem and overconsumption. For instance, apartments in multi-family buildings often split the water bill. In this paper, we analyzed how the introduction of apartment-level metering and billing (IMB) affects hot water consumption. We found that IMB decreases consumption by 26%. Heavy water users in the top consumption quartile account for most of the reduction. Moreover, our calculations show that IMB of hot water is a cost-effective policy tool, suggesting that the European Union Directive requiring IMB of hot water in multi-family buildings is a cost-effective environmental policy.

Our empirical results also imply that there is a serious common pool problem in water use when water is incorrectly priced. Overconsumption can be considerable even when the

[17] The Swedish CO_2 tax, applicable on fossil fuel, but not on electricity production, is currently 1.2 SEK per kg, which is high in an international comparison.
[18] This applies to contexts without a Pigouvian tax on CO_2 in electricity production.

number of heavy free-riders makes up a minority of the population. Previous literature has found effects of policy interventions based on provisions of more information about prices or based on non-pecuniary incentives. In comparison, pricing is a simpler and more powerful tool for efficient resource management and water conservation. In particular, introducing a marginal cost, reflecting the market price, when the price has been zero, appears to be highly effective.

Appendix A. IMB effect on temperature

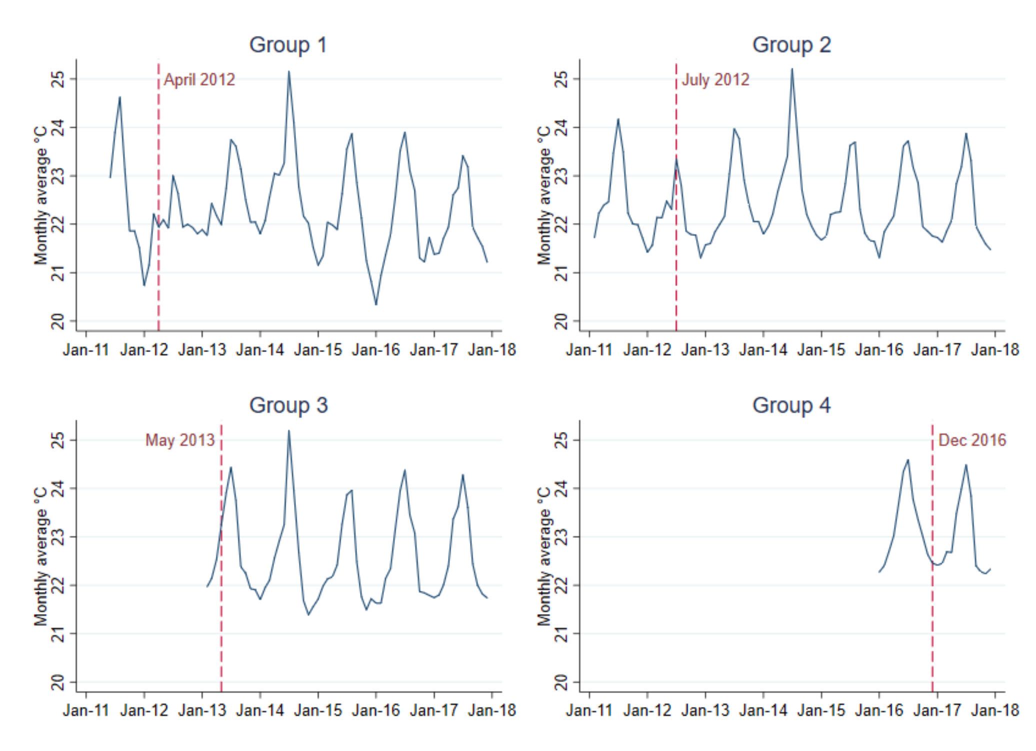

Figure A1. Monthly means of temperature by groups over time

Note: Dashed lines mark the first month following the IMB introduction dates in the four groups

Table A1. Panel estimates of IMB effects on temperature for the full sample

	(1)	(2)	(3)	(4)	(5)
IMB effect	0.046	0.003	0.051*	0.008	-0.202**
	(0.029)	(0.029)	(0.028)	(0.027)	(0.042)
Calendar month dummies	No	Yes	No	Yes	No
Date fixed effects	No	No	No	No	Yes
Apartment fixed effects	No	No	Yes	Yes	Yes

Notes: Temperature in degree Celsius is the dependent variable and IMB treatment is the main independent variable. Except for the dependent variable, Eq. (1) provides the regression equation. We report β, which is the effect of hot water IMB on temperature. Standard errors are clustered at the apartment level in parentheses. * $p<0.05$, ** $p<0.01$.

Appendix B. Accounting for mean reversion in our quartile analysis

To illustrate that we account for mean reversion, we use data for group 2 from 2014–2017 which is a placebo period without IMB introduction. We put a counterfactual placebo treatment date in the middle of the placebo period and then divide the apartments into consumption quartiles based (A) the pre-treatment average, (B) the post-treatment average, and (C) the mean of the pre- and post-treatment averages as in our quartile analysis in Section 8. In Figure A2, we plot consumption over time for the four quartiles. In Panel A, mean reversion manifests in terms of a positive trend in quartile 1 and a negative trend in quartile 4 in the post-treatment period. In Panel B, a less clear but opposite pattern is visible in the pre-treatment period. None of these patterns can be seen in the graph in Panel C.

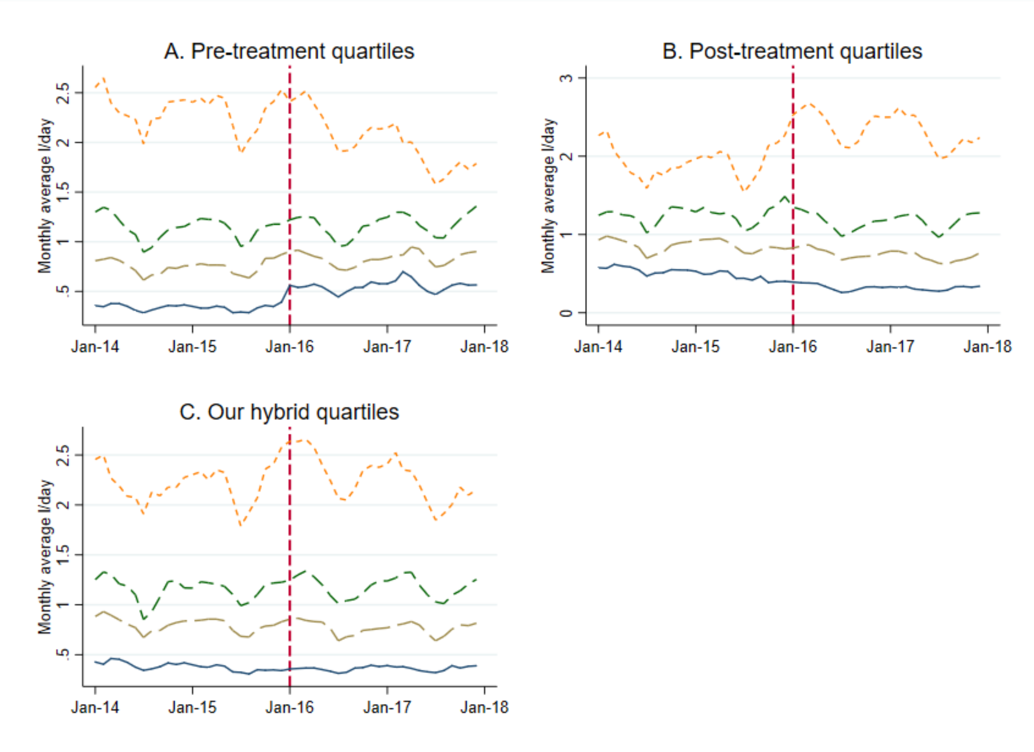

Figure A2. Water use by consumption quartiles for group 2 in a placebo period

Note: A dashed line marks the first month following the placebo treatment. We divide the apartments into four quartiles based on pre-treatment averages in Panel A, post-treatment averages in Panel B, and the mean of pre- and post-treatment averages in Panel C.

In Table A2, we report placebo estimates using the same specification as in the quartile analysis in Table 6, but replace the real IMB introduction date by our placebo treatment date. We do this for the three different quartile definitions. We see that only the quartile definition based on both pre- and post-treatment consumption deliver consistently insignificant point estimates of the placebo treatment effects across quartiles.

Table A2. Placebo estimates using different consumption quartile definitions

	(1) Quartile 1	(2) Quartile 2	(3) Quartile 3	(4) Quartile 4
	A. Quartiles based on pre-treatment water use			
IMB effect (%)	39.07**	7.024	-10.90*	-27.44**
	(11.86)	(6.153)	(4.737)	(4.292)
	B. Quartiles based on pre-treatment water use			
IMB effect (%)	-22.54**	-3.372	2.748	25.83**
	(5.860)	(6.057)	(5.975)	(8.926)
	C. Quartiles based on pre- and post-treatment water use			
IMB effect (%)	3.919	-0.683	3.530	-9.750
	(8.527)	(5.864)	(7.174)	(5.798)
Calendar month dummies	Yes	Yes	Yes	Yes
Apartment fixed effects	Yes	Yes	Yes	Yes

Notes: Log water use is the dependent variable and placebo treatment is the main independent variable. Eq. (1) provides the regression equation. We report $e^{\beta} - 1$ which is the percentage effect of placebo treatment on water use, and standard errors accounting for the same transformation are clustered at the apartment level in parentheses.

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