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Free riding and rebates for residential energy efficiency upgrades: A multi-country contingent valuation experiment

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ABSTRACT

The cost-effectiveness of energy technology upgrade programs critically depends on free riding. This paper assesses ex ante the effects of free riding on the cost-effectiveness of a rebate program that promotes the adoption of energy-efficient heating systems, relying on contingent valuation choice experiments carried out through identical representative surveys in eight EU Members States. The analysis distinguishes between strong and weak free riders: strong free riders already plan to adopt a new heating system in the next five years; weak free riders decide to purchase once propositioned with an attractive technology package (and therefore do not require a rebate to adopt). The reservation rebates for incentivized adopters (those who decide to adopt because of a rebate) differ substantially across countries. On average, they amount to approximately 40% of the heating system's purchasing price, suggesting generally high opportunity costs for premature upgrades. The reservation rebate and weak free-ridership vary with income, risk and time preferences, and environmental identity. At a rebate level that corresponds to half the purchase price of the offered heating system, the estimated share of free riders exceeded 50% for most countries, with a typically higher share of weak free riders than strong free riders. Specific rebate cost estimates (in €/tCO_2) differ considerably across countries, suggesting that cooperation can yield budgetary benefits.

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1. Introduction

Subsidies that incentivize the adoption of energy efficient technologies are commonly used by governments and energy companies to reach energy savings or greenhouse gas emission goals (de la Rue du Can et al., 2011, 2014; Galarraga et al., 2013, 2016). Surveys of the empirical literature typically conclude that subsidies, such as rebates and subsidized loans, spur the adoption of energy efficient technologies (e.g. Markandya et al., 2014; Datta and Filippini, 2016). Subsidies may also help accelerate the replacement of energy-using technologies, such as appliances or heating systems, before they reach the natural end of their working life. Such premature technology upgrades may be required to meet ambitious climate policy targets, particularly for the residential building sector, which is generally considered to represent high potential for energy savings (IEA, 2016). In practice, subsidies are often combined with information and communication programs that help customers overcome a lack of information on available efficiency upgrades, prohibitive transaction costs, or a lack of awareness (e.g., Stern et al., 1986; Blumstein, 2010; Allcott and Taubinsky, 2015; Gillingham and Palmer, 2014).

The design and evaluation of subsidy programs that promote energy efficient technologies are generally complicated by self-selection, rebound effects, moral hazard (consumers deferring adoption to wait for a financial incentive program), and free riding (Hartman, 1988; Gillingham et al., 2006; Alberini et al., 2014). Failure to account for these issues results in an overestimation of policy effectiveness (e.g. Joskow and Marron, 1992). Free riding, the focus of this study, occurs when subsidies are paid to customers who would have purchased the technology even without the subsidy. Free-ridership has been estimated in a variety of ways in previous ex post studies of utility demand side management (DSM) and tax credit programs for residential energy efficiency upgrades in North America (Joskow and Marron, 1992; Malm, 1996; Loughran and Kulick, 2004; Boomhower and Davis, 2014) and Europe (Grösche and Vance, 2009; Nauleau, 2014; Alberini et al., 2014). These studies find that free-rider shares among program beneficiaries range from 50% to 90%. For governments and utilities, it is rarely feasible to distinguish among beneficiaries who needed or did not need the subsidy to engage in energy efficient behavior. Similarly, the economic evaluation literature presumes a non-discrimination principle of incentive allocation: those who allocate the rebate cannot - if not for ethical reasons then for reasons of prohibitive administrative costs - distinguish between free riders and non-free riders when granting subsidies to consumers who purchase eligible efficiency upgrades. In

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addition, when subsidies are part of a policy package (usually also involving accompanying information programs), evaluations typically cannot identify the effects of individual policies on program effectiveness and program costs. For example, program evaluations typically do not distinguish customers who were planning to invest in an energy efficient technology anyway from customers who were not originally planning to invest in such a technology but decided to do so after being informed.

The overall objective of this paper is to do an ex ante assessment of the effects of free riding on the cost-effectiveness of a rebate program that incentivizes the premature adoption of energy-efficient heating systems in eight EU Member States. Unlike previous studies, we distinguish the effects of two types of free riders, which we name strong and weak free riders respectively. Strong free riders are households that were planning to invest in a new heating system anyway; weak free riders are households that were not originally planning to invest in a heating system but decided to do so after receiving information about an attractive technology package (and therefore only needed awareness of technology, not of the rebate). We effectively separate the effects of providing information from the effects of offering rebates. Further, we explore the factors explaining weak free-ridership and the rebate level required to adopt a new heating system. Our findings allow for an analysis of the cost-effectiveness of rebate programs across countries, and assess the relevance of each type of free riding for differences in cost-effectiveness across countries.

Our empirical analysis relies on contingent valuation choice experiments carried out through representative surveys of around 15,000 households in eight EU Members States (France, Germany, Italy, Poland, Romania, Spain, Sweden, and the United Kingdom (UK)). Together, these eight countries account for about 80% of EU population, energy use, and greenhouse gas emissions. Respondents' choices are used to estimate (for each country) the probability that households upgrade their heating system as a function of the rebate offered, and to construct curves for the specific rebate costs (in €/tCO_2) based on free-rider shares, which are compared across countries.

The remainder of the paper is organized as follows. Section 2 presents the methodology, describing an analytical model to evaluate the effectiveness of a rebate policy distinguishing between strong and weak free riders, the multi-country survey, and the choice experiment. Section 3 presents the results, showing findings for rebate levels across countries and for the determinants of the rebate level and weak free-ridership. Section 3 also includes simulation analyses on the effects of strong and weak free riding on the cost-effectiveness of rebates across countries. Finally, Section 4 summarizes and discusses our main findings and identifies policy implications.

2. Methodology

In this section, we first present a simple analytical model for evaluating the effectiveness of a rebate policy while distinguishing between strong and weak free riders. Then, we describe our survey, our choice experiment, and the econometric model that we employed to estimate the rebate level and to conduct simulations. Finally, we present the data by including the descriptive statistics of the choice experiment and the household and respondent characteristics used as covariates in our econometric model.

2.1. Analytical model of rebate effectiveness and free riding

The model presented in this section will later be parameterized with econometric estimates based on a contingent valuation survey. Constructing specific rebate cost curves as a function of the rebate level allows us to simulate the effects of free riding on the cost-effectiveness of the rebate program for premature adoption of an energy efficient technology (here: heating).

The specific rebate c costs are the average CO_2 abatement costs of the rebate program:

$$c = C/\Delta E \tag{1}$$

C captures total program costs, i.e. the total expenditure for rebate payments, and ΔE is the total additional CO_2 emissions saved by the rebate program. The non-discrimination principle implies that all adopters receive the rebate:

$$C = N_{adopt} \times R = \left(N_{ia} + N_{wfr} + N_{sfr}\right) \times R \tag{2}$$

where R stands for the rebate offered and N_{adopt} is the total number of households adopting, comprised of (i) the number of incentivized adopters N_{ia}, i.e. those adopting only if $R > 0$; (ii) the number of weak free riders N_{wfr}, i.e. those adopting once made aware of an attractive technology package; and (iii) the number of strong free riders N_{sfr}, i.e. those adopting independent of a rebate or additional information. Let the number of strong free riders be defined as:

$$N_{sfr} = N_{pop} \times a \tag{3}$$

where N_{pop} is the total number of households in the population, and a is the share of strong free riders. Similarly, we denote the number of incentivized adopters:

$$N_{ia}(R) = N_{pop} \times b(R), \text{ for } R > 0 \tag{4}$$

where $b(R)$ is the probability of adoption, i.e. Pr(adoption|R); $b(R)$ is a function of the rebate R with $b'(R) > 0$ (for $R > 0$). The number of weak free riders is then:

$$N_{wfr} = N_{pop} \times b(0) \tag{5}$$

where $b(0)$ defines the share of weak free riders in the population. Program costs are:

$$C = R \times N_{pop}[a + b(0) + b(R)] \tag{6}$$

The additional CO_2 emissions saved by incentivized adopters can be written as:

$$\Delta E = N_{ia}(R) \times \Delta e \times \gamma = b(R) \times N_{pop} \times \Delta e \times \gamma \tag{7}$$

where Δe is end-use energy savings per replacement, and γ is the CO_2 emissions per unit of energy. We may then rewrite the specific rebate costs from Eq. (1) as:

$$c = \frac{C}{\Delta E} = \frac{R \times [a + b(0) + b(R)]}{b(R) \times \Delta e \times \gamma} \tag{8}$$

As further detailed in Section 2.4, we employ a double-bounded willingness-to-accept choice experiment and interval data model estimation to predict the probability of adoption and to estimate $b(R)$ and $b(0)$.

2.2. Survey

The survey was implemented by Ipsos GmbH (a German polling company) via computer assisted web interviews (CAWI), using existing household panels from Ipsos. A total of 15,055 participants from eight EU countries (France, Germany, Italy, Poland, Romania, Spain, Sweden, UK) completed the survey. In each country, participants were selected via quota sampling to be representative for the country in terms of gender, age (between 18 and 65 years), and region; only respondents who said that they were involved in their household's investment decisions for utilities, heating, and household appliances were qualified for the survey. Interviews were carried out between July and August 2016.

All interviews were translated from the original language (English) to the language of each country by professionals, and back translated subsequently to test for and eliminate any differences that could be attributed to language.

Our survey contained questions on the adoption of energy-efficient technologies, as well as questions designed to assess personality traits and attitudes via established scales. The survey included items that reflect patience (Falk et al., 2016), willingness to take risks (Dohmen et al., 2010, 2011; Falk et al., 2016), cognitive reflection (Frederick, 2005), and environmental identity (Whitmarsh and O'Neill, 2010).[1] Socio-demographic information was gathered both at the beginning of the questionnaire (to ensure that quota requirements were met), and at the end of the questionnaire.

2.3. Choice experiment

To evaluate the potential effectiveness of a rebate for the replacement of heating systems, we conducted a choice experiment with a subsample of home-owner respondents. Of all 15,055 respondents, 10,334 were home owners. Owners of buildings that were built before the year 2000 who indicated that they had changed their heating in the past 10 years were asked questions about the reasons for the replacement, the type of their new heating system, and their purchasing criteria, but were then discarded from the free-rider choice experiment to mitigate adverse selection. The remaining 7494 owners were then asked whether they planned to replace their heating system in the next 5 years. Those who answered “yes” were identified as strong free riders (N_{sfr}): households that were planning to purchase anyway, regardless of the rebate program. Those who answered “no” were asked to participate in a simple choice experiment.

The structure of our choice experiment questions is outlined in Fig. 1. We adapted the choice experiment design from Alberini and Bigano (2015), who employ a similar experiment to evaluate the effectiveness of subsidies for the replacement of heating systems in Italy. The choice experiment proposed a hypothetical heating system replacement with a fixed replacement cost, and a fixed amount of savings on energy costs that would accumulate over a given number of years.

The attribute *savings* represents the expected total monetary benefit of the replacement. We chose to use a fixed amount of savings rather than an annual amount or percentage reduction because a fixed amount does not require the respondents to calculate the trade-off costs and benefits.

The attribute savings *duration* adds a time discounting aspect to the expected total monetary benefits. Duration represents the number of years over which the replacement could be expected to reduce energy expenditures for heating and over which the savings would accumulate.

The replacement cost was fixed at 2000 euros (equal to Alberini and Bigano, 2015). The level of *savings* varied randomly between 200, 400, 600, and 800 euros. The level of savings *duration* varied randomly between 10, 15, and 20 years. These attribute levels result in 12 different investment propositions.

The levels of the attributes were chosen to be internally consistent and reflective of (by approximation) realistic values. The values can be compared to expected costs and savings for a replacement of the most common type of heating system in the EU - a natural gas boiler[2] – with a more efficient, commonly available off-the-shelf version of itself. This enables to compare our results with previous studies that used similar attribute levels (i.e. Alberini and Bigano, 2015). The 2000-euro replacement cost is at the lower end of the cost spectrum but remains realistic (e.g. Alberini et al., 2014; E3MLab 2011, p. 42). The savings duration levels span a conservative range of the economic life of a gas boiler.[3] The total range represented by 12 combinations of savings and duration then corresponds, for example, to an efficiency gain of 1%–10% in Germany, 2%–15% in the UK, and 5%–42% in Spain.[4]

Each respondent was shown one proposition and could either accept or reject it. Respondents who rejected the initial proposition were offered, at random, one of six rebates and were asked if they would adopt the proposed heating system at the given rebate level. Rebates varied randomly among 100, 200, 300, 500, 800, or 1000 euros.[5] Since the values for the level of the rebate, savings, and duration were all randomly assigned to respondents, our design mimics a randomized controlled experiment.

The choice options yielded three types of respondents:

Type 1 (observed weak free riders): Respondents who accepted the initial offering. For this type of respondent, the latent reservation incentive is between -∞ (or negative disposable income) and 0. These are therefore observed weak free riders, i.e., households who were not planning to purchase a heating system but decided to do so when informed about a technology option.

Type 2 (incentivized adopters): Respondents who rejected the initial offering but accepted when the rebate was offered. For this type of respondent, the latent reservation incentive is between 0 and the offered rebate.

Type 3 (non-adopters): Respondents who rejected both the initial offering and the rebate. For this type of respondent, the latent reservation incentive is between the offered rebate and ∞.

2.4. Econometric model

We use an adapted double-bounded willingness-to-pay approach (Cameron and James, 1986; Hanemann et al., 1991) to estimate the probability of adoption as a function of the rebate offered. Similar to Alberini and Bigano (2015), the adaptation reflects a focus on willingness-to-accept a subsidy rather than on willingness-to-pay.

We assume that a household i has a reservation rebate level R_i^*. A rebate $R_i \geq R_i^*$ would lead a household to adopt the technology; a rebate $R_i < R_i^*$ would lead to rejection. R_i^* is a function of both the technology package and the household characteristics. It can be written as:

$$R_i^* = \alpha + \boldsymbol{x}_i \boldsymbol{\beta} + \boldsymbol{z}_i \boldsymbol{\delta} + \varepsilon_i \tag{9}$$

where $\boldsymbol{x}_i$ defines the technology package consisting of the annual savings s_i and the duration of the savings t_i, $\boldsymbol{z}_i$ is a set of control variables defining a household's characteristics, and ε_i is the normally distributed error term with standard deviation σ. The household characteristics comprise both socio-demographic and attitudinal variables, which are described in Section 2.5 and Table 3.

R_i^* cannot be observed, but it can be estimated in a double bounded contingent valuation model. The probability that R_i^* lies between the lower (R_i^L) and upper bound (R_i^U) obtained from the household's

[1] Annex I reports the exact scales used.

[2] According to a recent study for the European Commission, natural gas boilers account for 40% of the heating technology stock in the EU in 2012 (Fleiter et al. 2016, p.15). Also in our survey, gas boilers are the most common replacement type (40%) among the options proposed, but their share among the heating systems substituted over the past 10 years varies between 20% (Poland) and 79% (UK). An exception is Sweden with 3%.

[3] For the technical lifetime of an individual residential gas boiler, 22 years seems to be a consensual duration (e.g. Connolly et al., 2014; Fleiter et al. 2016, p.11). Economic life tends to be shorter.

[4] Percentages based on own calculations, using data from ODYSSEE (2016) on gas consumption for space heating and the share of residences using natural gas as an energy source for heating, and data from Eurostat (2016b) on natural gas prices for domestic users including levies and taxes. Data are from 2010.

[5] Since the survey was conducted in countries with different currencies, we had to adjust the monetary amounts. Moreover, we aimed to keep the relative value of monetary amounts similar between countries in terms of purchasing power. To this end, we applied the following exchange rates: Poland 1€ = 3 PLN; Romania 1€ = 3 RON, Sweden 1€ = 10 SEK, and UK 1€ = 1 GBP. In all Euro-zone countries, the monetary amounts shown to respondents were the same, for Sweden, UK, Poland, and Romania, monetary amounts were multiplied with the respective factors.

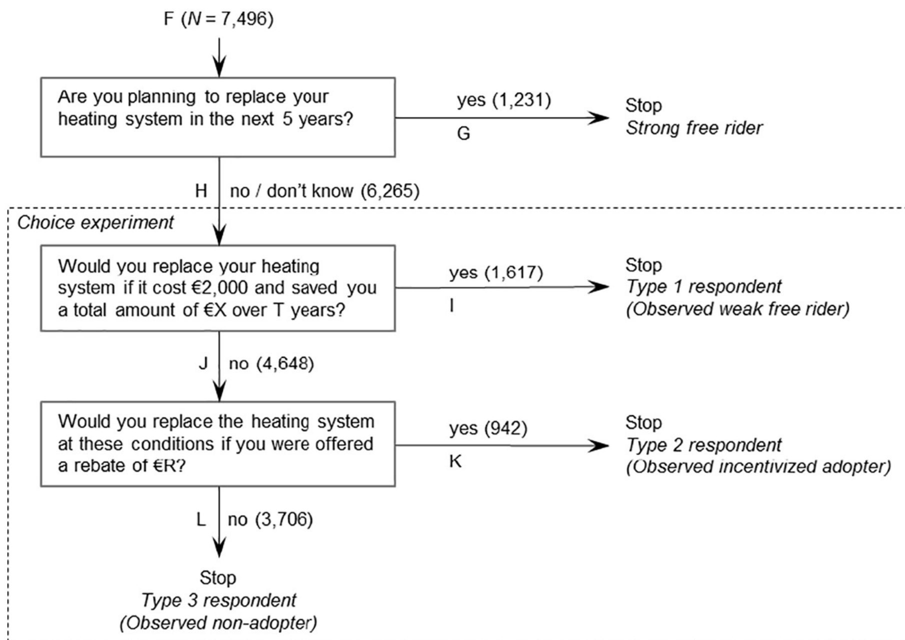

Fig. 1. Structure of the future adoption and choice experiment questions. The numbers in brackets represent the number of respondents choosing that specific option. The capital letters correspond to the rows in Table 1.

responses in the choice experiment is written as the following interval data model:

$$\begin{aligned}\Pr\left(R_i^L < R_i^* \le R_i^U\right) &= \Pr\left(R_i^L < \alpha + \boldsymbol{x}_i\boldsymbol{\beta} + \boldsymbol{z}_i\boldsymbol{\delta} + \varepsilon_i \le R_i^U\right) = \\ \Pr\left(\left(R_i^L - (\alpha + \boldsymbol{x}_i\boldsymbol{\beta} + \boldsymbol{z}_i\boldsymbol{\delta})\right)/\sigma < \varepsilon_i/\sigma \le \left(R_i^U - (\alpha + \boldsymbol{x}_i\boldsymbol{\beta} + \boldsymbol{z}_i\boldsymbol{\delta})\right)/\sigma\right) &= \\ \Phi\left(\left(R_i^U - E(R_i^*)\right)/\sigma\right) - \Phi\left(\left(R_i^L - E(R_i^*)\right)/\sigma\right) &= \Phi^U - \Phi^L\end{aligned} \quad (10)$$

where Φ denotes the standard normal cumulative density function, and $E(R_i^*)$ is the expected value of the threshold subsidy level.

For the three types of respondents (Fig. 1), Φ^U and Φ^L are as follows:

For type 1 respondents, $\Phi^U = \Phi((0 - E(R_i^*))/\sigma) = \Phi(-E(R_i^*)/\sigma)$ and $\Phi^L = \Phi(-\infty) = 0$.

For type 2 respondents, $\Phi^U = \Phi((R_i - (R_i^*))/\sigma)$ and $\Phi^L = \Phi((0 - E(R_i^*))/\sigma) = \Phi(-E(R_i^*)/\sigma)$.

For type 3 respondents, $\Phi^U = \Phi(\infty) = 1$ and $\Phi^L = \Phi((R_i - E(R_i^*))/\sigma)$.

We use a maximum likelihood procedure to estimate the coefficients α, $\boldsymbol{\beta}$, and $\boldsymbol{\delta}$. With these coefficients, we can then predict the probability of adoption for the sample and obtain the free-rider shares. Given data availability, we slightly redefine the share of strong free riders compared to Eq. (3) as:

$$a = N_{out}/N_{sample}, \quad (11)$$

with $N_{out}$the number of people stating an intention to adopt a new heating system in the next five years.

$$\begin{aligned}b(R) &= \Pr(\text{adoption} \mid R_i > 0) \times \left[N_{exp}/N_{sample}\right] \\ &= \Phi\left(\left(R_i - E(R_i^*)\right)/\sigma\right) \times \left[N_{exp}/N_{sample}\right]\end{aligned} \quad (12)$$

$$\begin{aligned}b(0) &= \Pr(\text{adoption} \mid R_i = 0) \times \left[N_{exp}/N_{sample}\right] \\ &= \Phi\left(\left(0 - E(R_i^*)\right)/\sigma\right) \times \left[N_{exp}/N_{sample}\right]\end{aligned} \quad (13)$$

N_{exp} is the size of the subsample eligible for the choice experiment, i.e. those who had not and were not planning to adopt within the given timeframe, and N_{sample} is the full sample size, i.e. $N_{exp} + N_{out}$. Note that Eq. (13) yields the predicted weak free riders. Unlike observed weak free riders, using Eq. (13) allows us to calculate weak free riding independent of the range of subsidies offered in the choice experiment.

2.5. Data

In this section, we present the descriptive results of the survey questions used to select our sample (Table 1), the choice experiment (Table 1, Table 2), and the household characteristics used in our econometric model (Table 3).

2.5.1. Sample selection and respondents' choices

This project was part of a broader survey including 15,055 households in eight EU countries. Row A in Table 1 shows that respondents are uniformly distributed over the countries, except for in Romania and Sweden, where the sample was smaller. For this study, the focus was on households with ownership over their primary residence (row B), which represent approximately two-thirds of all sampled households ($N = 10{,}334$). Of the home owners, 52% lived in buildings predating 2000 and had not replaced their heating systems in the past 10 years (D); 21% lived in buildings built in 2000 or after (E). These 7496 home owners were considered potential beneficiaries of a rebate program for heating system replacement (F) and were asked if they planned to replace their heating system in the next 5 years. Approximately 1 in 8 (1231) said they were (G). These are the strong free riders, who would benefit from a rebate program but would have adopted anyway.

We ran the choice experiment with the remaining 6265 homeowners (varying between 419 and 1132 per country). Approximately 26% (18–32%) of those offered an investment proposition accepted it (Type 1 respondents). The remaining 74% (68–82%) were offered a rebate, which 15% (11–21%) accepted (Type 2 respondents) and 59% (50–68%) rejected (Type 3 respondents).

Table 2 shows that the likelihood of agreeing to the hypothetical investment proposition increases with the level of the rebate and, hence, that responses are internally consistent.

2.5.2. Covariates

Table 3 contains descriptive information and measurements of the household characteristics that make up the control variables vector $\boldsymbol{z}_i$

Table 1
Sample filtering and descriptive country-level results of choice experiment (frequencies).

	(Sub)sample filter	All countries	FR	DE	IT	PL	RO	ES	SE	UK
A	Households surveyed	15,055	2000	2002	2000	2008	1529	2001	1515	2000
B	Home owners	10,334	1286	885	1595	1678	1204	1548	811	1327
	B/A	0.69	0.64	0.44	0.80	0.84	0.79	0.77	0.54	0.66
C	…in building built before 2000	8200	955	709	1277	1317	1039	1022	711	1170
	C/B	0.79	0.74	0.80	0.80	0.78	0.86	0.66	0.88	0.88
D	…who did not replace heating system in past 10 years	5362	584	458	771	950	541	773	494	791
	D/B	0.52	0.45	0.52	0.48	0.57	0.45	0.50	0.61	0.60
E	…in building built in 2000 or later	2134	331	176	318	361	165	526	100	157
	E/B	0.21	0.26	0.20	0.20	0.22	0.14	0.34	0.12	0.12
F = D + E	Subsample for questions on future adoption	7496	915	634	1089	1311	706	1299	594	948
	F/B	0.73	0.71	0.72	0.68	0.78	0.59	0.84	0.73	0.71
G	…planning to replace in the next 5 years (strong free riders)	1231	114	126	195	179	287	144	53	133
	G/F	0.16	0.12	0.20	0.18	0.14	0.41	0.11	0.09	0.14
H = F− G	…not planning to replace in the next 5 years	6265	801	508	894	1132	419	1155	541	815
	H/F	0.84	0.88	0.80	0.82	0.86	0.59	0.89	0.91	0.86
I	Accepted proposition (Type 1)	1617	219	139	263	343	134	269	104	146
	I/H	0.26	0.27	0.27	0.29	0.30	0.32	0.23	0.19	0.18
J = H− I	Rejected proposition	4648	582	369	631	789	285	886	437	669
	J/H	0.74	0.73	0.73	0.71	0.70	0.68	0.77	0.81	0.82
K	Accepted rebate (Type 2)	942	101	57	134	184	74	154	69	169
	K/H	0.15	0.13	0.11	0.15	0.16	0.18	0.13	0.13	0.21
L = J− K	Rejected rebate (Type 3)	3706	481	312	497	605	211	732	368	500
	L/H	0.59	0.60	0.61	0.56	0.53	0.50	0.63	0.68	0.61

in Eq. (9). The variables *Gender*, *Age*, *Education*, *Income*, and *HHsize* (household size) capture socio-demographic characteristics of our sample. In the survey, education levels of the respondents were indicated as 1 "No degree or certificate", 2 "Trade/Vocational certificate or equivalent", 3 "High school or equivalent", and 4 "Higher education degree or equivalent (College, University...)". The coded *Education* dummy takes on the value of 1 if a respondent's education level is equal to or above their country's median education level, and 0 otherwise. To measure *Income*, the questionnaire asked respondents to indicate their household's approximate annual income after tax, i.e. including wages, government and company pensions and benefits, and investment dividends and rents. Respondents had to choose among 12 ranges of income, which differed by countries. We let the *Income* variable take the value of the midpoint of the chosen income level and used the lower bound if a respondent selected the highest open-ended level. To save observations, we replaced missing values by the country mean and added a control dummy *Income missing*. Across countries, differences in income are substantial, varying by a factor of 5 between Romania and the UK.

Four additional variables control for personal and attitudinal traits (see Annex I for measurement scales). First, we included *WTWait* (willingness to wait) to account for differences in time discounting across respondents, as the substitution of a new more efficient heating system involves an upfront investment followed by lower fuel expenditures. Empirical findings by Newell and Siikamäki (2015) or Allcott and Taubinsky (2015), for example, suggest that higher time discounting is negatively related with energy efficient technology adoption. More patient respondents are therefore expected to be more willing to replace their old heating system and to require lower rebates. In our sample, Romanian and French respondents appear to be the most and least willing to wait, respectively. Second, *WTRisk* (willingness to take risks) was included to account for variance in risk preferences. The realized expenditure savings associated with a new heating system depend on uncertain factors such as future fuel prices, technology performance, or regulation (e.g. fuel tax rates). Such an investment can be considered as risky and therefore risk preferences are expected to affect adoption. More risk-averse individuals have been found to be less likely to adopt energy efficient technologies (e.g. Farsi, 2010; Qiu et al., 2014). Thus, respondents who are more willing to take risks are expected to be responsive to lower rebates. In our sample, German and Romanian respondents are found to be the least and most willing to take risks, respectively. Third, because previous research has shown the importance of controlling for cognitive reflection when studying the impact of time and risk preferences (Frederick, 2005; Dohmen et al., 2010), *CRT* (cognitive reflection test) was included. Respondents in the three richest countries (Germany, Sweden and the UK) recorded above-average CRT scores. Finally, we implemented *ENV_ID* (environmental identity) to control for differences in respondents' environmental attitudes. Since a new, more efficient heating system lowers resource use and polluting emissions, pro-environmental attitudes may affect adoption. Among others, Mills and Schleich (2012, 2014) found a positive correlation between environmental attitudes and adoption of energy efficient technologies. Thus, respondents with stronger environmental attitudes are expected to require a lower rebate to adopt. In our sample, environmental identity appears weaker in the richer countries.

Table 2
Proportion of "yes" responses by rebate offered and by country.

		All countries	FR	DE	IT	PL	RO	ES	SE	UK
	N	*4648*	*582*	*369*	*631*	*789*	*285*	*886*	*437*	*669*
Rebate (€)	100	0.06	0.02	0.05	0.03	0.12	0.07	0.04	0.03	0.11
	200	0.09	0.10	0.07	0.06	0.12	0.06	0.10	0.11	0.10
	300	0.10	0.09	0.06	0.09	0.11	0.15	0.06	0.03	0.17
	500	0.21	0.20	0.16	0.25	0.27	0.29	0.14	0.09	0.25
	800	0.30	0.18	0.25	0.38	0.30	0.38	0.30	0.31	0.36
	1000	0.40	0.41	0.30	0.44	0.42	0.52	0.33	0.30	0.49
	Total	0.20	0.17	0.15	0.21	0.23	0.26	0.17	0.16	0.25

3. Results

We first present our econometric findings on rebate levels across countries as well as determinants of the reservation rebate level and weak free-ridership respectively. Using econometric parameter estimates we then carry out simulations to provide further insights into the impact of the two types of free riders on the cost-effectiveness of rebates (for upgrading heating systems) across countries.

3.1. Econometric results for reservation rebate levels

To simply estimate the mean and median reservation rebate level, all variables of the technology package $\boldsymbol{x_i}$ and household characteristics $\boldsymbol{z_i}$ were dropped from Eq. (9). Results for this reference model appear in Table 4. In the *all-countries model*, where data from all countries are

Table 3
Covariates: description, measurement, and descriptive statistics: means with standard deviations in parentheses.

Variable	Description	Measurement	All countries	FR	DE	IT	PL	RO	ES	SE	UK
N			*6265*	*801*	*508*	*894*	*1132*	*419*	*1155*	*541*	*815*
Gender	A respondent's gender	Dummy (=1 if male)	0.509 (0.499)	0.495 (0.499)	0.543 (0.500)	0.508 (0.500)	0.501 (0.500)	0.513 (0.500)	0.525 (0.499)	0.523 (0.499)	0.476 (0.499)
Age	A respondent's age	Years	42.006 (12.693)	43.329 (12.799)	43.240 (13.052)	43.597 (12.591)	38.686 (11.623)	36.577 (10.737)	42.969 (12.009)	44.584 (13.668)	42.521 (13.477)
Education	A respondent's education level	Dummy (=1 if ≥country median)	0.659 (0.474)	0.611 (0.487)	0.545 (0.498)	0.829 (0.375)	0.563 (0.496)	0.725 (0.446)	0.583 (0.493)	0.894 (0.307)	0.638 (0.480)
Income	A household's annual income after tax	Midpoint of 11 income intervals and lower bound of highest interval (k€)	32.401 (22.519)	33.104 (18.707)	44.930 (19.323)	30.804 (15.970)	15.409 (9.214)	11.327 (9.762)	28.311 (14.912)	50.260 (24.096)	54.100 (27.238)
Income missing	Indicates if household income data not provided	Dummy (=1 if an observation for Income is missing)	0.168 (0.374)	0.148 (0.355)	0.151 (0.358)	0.189 (0.391)	0.215 (0.411)	0.112 (0.315)	0.208 (0.406)	0.116 (0.321)	0.119 (0.324)
HHsize	The size of a respondent's household	Number of household members	2.705 (1.369)	2.550 (1.273)	2.291 (1.210)	3.102 (1.265)	3.130 (1.445)	3.028 (1.818)	3.011 (1.224)	2.198 (1.240)	2.653 (1.338)
WTWait	A respondent's level of patience	z-score based on responses to 1 scale item[a]	0.000 (1.000)	−0.160 (1.002)	−0.031 (0.956)	0.067 (0.958)	0.043 (1.064)	0.196 (1.223)	0.034 (0.918)	−0.062 (0.993)	0.031 (0.969)
WTRisk	A respondent's willingness to take risks	z-score based on responses to 1 scale item[a]	0.000 (1.000)	−0.005 (0.936)	−0.192 (0.944)	−0.110 (0.982)	0.089 (1.003)	0.268 (1.045)	0.115 (0.955)	0.058 (1.006)	−0.045 (1.081)
CRT	A respondent's cognitive reflection ability	z-score based on responses to 3 Cognitive Reflection Test items[a]	0.000 (1.000)	−0.013 (1.000)	0.178 (1.025)	−0.245 (0.773)	−0.057 (1.018)	−0.077 (0.996)	−0.127 (0.966)	0.14 (1.041)	0.073 (1.040)
ENV_ID	A respondent's environmental identity	z-score based on responses to 4 scale items[a]	0.000 (1.000)	0.143 (0.884)	−0.085 (0.977)	0.329 (0.855)	0.008 (0.957)	0.085 (1.014)	0.224 (0.921)	−0.386 (1.091)	−0.165 (1.070)

[a] See Annex I for a more detailed description of the scales used to elicit these characteristics.

Table 4
Results for reference model (*p*-value in parentheses).

	All countries	FR	DE	IT	PL	RO	ES	SE	UK
Rebate	775***	889***	990***	665***	437***	354***	995***	1212***	876***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Sigma	1205***	1477***	1650***	1224***	861***	755***	1367***	1395***	972***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
N	6265	801	508	894	1132	419	1155	541	815
Log likelihood	−5736.4	−710.3	−444.5	−820.4	−1102.7	−401.8	−998.8	−435.9	−729.9

*** $p < .01$.

pooled, the mean and median reservation rebate is 775 euros with a standard deviation *Sigma* of 1205 euros. For the individual models, which only use country-specific observations, we find the lowest mean and median reservation rebates for Romania and Poland, and the highest for France, Germany, and Sweden. In the *all-countries* model and in most individual models, the mean and median reservation rebate corresponds to nearly 40% of the heating system's purchasing price of 2000 euros, suggesting generally high opportunity costs for premature heating system replacement. The standard deviation of 1205 euros indicates that a substantial proportion of the subsample of potential adopters have zero or negative estimated reservation rebates: the weak free riders. This is the case for each country.

3.2. Econometric results for determinants of reservation rebate and weak free-ridership

Table 5 reports results for the *all-countries* model, when all variables of the technology package $\boldsymbol{x_i}$ and household characteristics $\boldsymbol{z_i}$ are included in Eq. (9). As expected, the reservation rebate is lower when the *savings* offered are higher. On average, each additional euro of total *savings* over a heating system's economic life lowers the reservation rebate by about 0.17 euros. *Duration* exhibits the expected positive sign, but is not statistically significant at conventional levels.

Regarding the relationships between the different household characteristics and the reservation rebate, the coefficients of *gender*, *age*, and *education* are not statistically significant at conventional levels. Somewhat counterintuitively, the reservation rebate is positively related to *income*. Hence, weak free-ridership (i.e., respondents with predicted $R^* \leq 0$) is negatively related to income. Per 1000 euros increase in income, a household requires a rebate that is about 2.6 euros more. Higher-income households may be less interested in the relatively small cash flow savings the hypothetical replacements would yield.

Table 5
Correlations of the reservation rebate with socio-demographic and attitudinal variables.

Variable	Coeff.	*p*-value
Savings	−0.17**	(0.041)
Duration	4.44	(0.349)
Gender	−10.45	(0.772)
Age	1.13	(0.443)
Education	−5.18	(0.897)
Income	2.60**	(0.013)
Missing income	34.76	(0.467)
HHsize	−60.78***	(0.000)
WTWait	−91.23***	(0.000)
WTRisk	−127.12***	(0.000)
CRT	131.17***	(0.000)
ENV_ID	−98.49***	(0.000)
FR	68.12	(0.399)
IT	21.86	(0.787)
PL	−111.92	(0.172)
RO	−152.96	(0.125)
ES	275.28***	(0.000)
SE	226.34**	(0.012)
UK	177.07**	(0.028)
Constant	751.91***	(0.000)
Sigma	1134.34***	(0.000)
N	6265	
Log likelihood	−5554	

*** $p < .01$.
** $p < .05$.

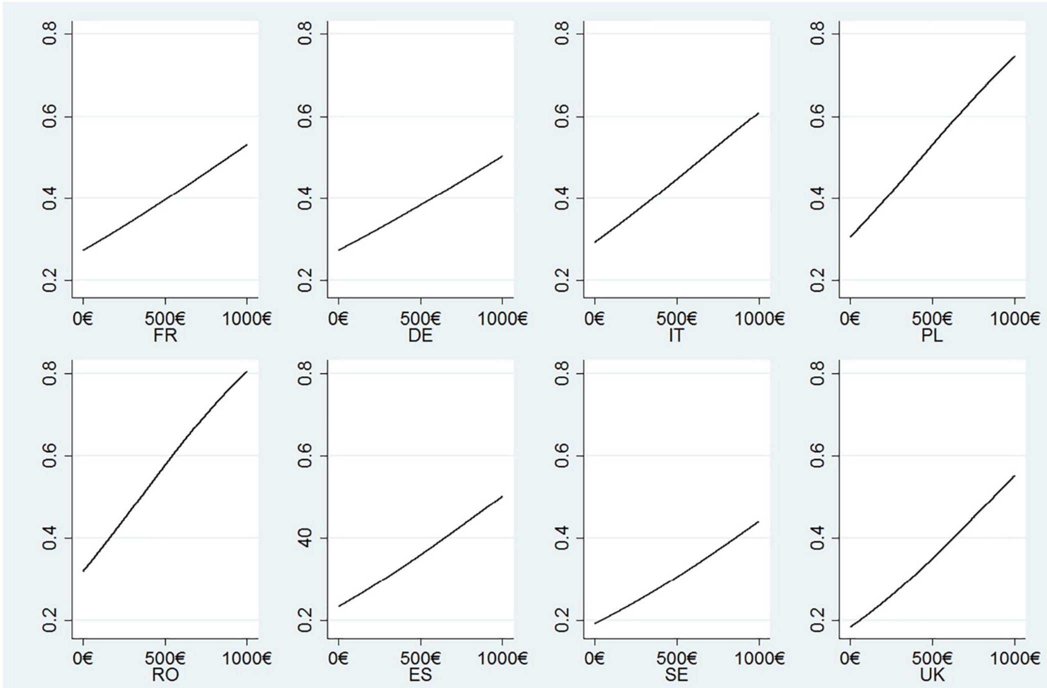

Fig. 2. Estimated probability of adoption as a function of the rebate (in €).

Whether a household did or did not report its income is not significantly correlated with the reservation rebate.[6] The coefficient on *HHsize* suggests that each additional household member lowers the rebate by almost 61 euros. As expected and consistent with prior empirical evidence, respondents with a higher *willingness to wait* and *willingness to take risks* require a lower rebate and are less prone to be predicted weak free riders. Interestingly, respondents with a higher *cognitive reflection* score (CRT) demand a higher rebate and are less prone to be weak free riders. Arguably, respondents with a high cognitive reflection score who stated that they did not intend to adopt a new heating system (within the next 5 years) grounded their statement in rational decision-making based on sufficient information; altering this decision would lead to a relatively high welfare loss, thus requiring a higher rebate for compensation. Finally, and as expected, a higher *environmental identity* translates into a lower rebate. Thus, aside from income, most household characteristics exhibit expected relationships with the reservation rebate, and hence with predicted weak free-ridership.[7,8]

3.3. Simulations

We perform simulations to gain further insights into the role of weak and strong free riders on cost-effectiveness of the rebate and into differences across countries. For these simulations, we use the results of the interval data model estimations presented in Table 4. Hence, the probability of adoption depends on the rebate level only. For simplicity, we excluded the savings amount and duration from the simulations because they would enter the subsequent simulations as constant factors only and would not alter the qualitative findings. Moreover, the maximum likelihood estimations showed that they did not correlate significantly with the reservation rebate across all countries.

3.3.1. Rebate effectiveness (incentivized adopters)

Fig. 2 plots the probability of adoption as a function of the rebate level Pr(adoption | R_i) for each country. Higher rebates increase adoption probability at a rate of between 4.2 percentage points in Sweden and 10 percentage points in Romania per 200 euros increase (i.e. 10% of the proposed purchase price).[9] Steeper curves reflect larger changes in adoption rates in response to a change in the rebate level. Thus, the results show that raising a rebate by a given amount would lead to particularly large increases in the share of incentivized adopters in Romania, Poland, or the UK, and to relatively small increases in Germany, France, or Sweden.

3.3.2. Free riders

The curves' intercepts with the ordinate in Fig. 2 depict the predicted share of weak free riders in the subsample participating in the experiment (N_{exp}), i.e. the share of those whose reservation rebate is zero or lower. Accordingly, the average weak free-rider share is around 20% of the subsample, lowest for the UK (18.7%), Sweden (19.2%), and Spain (23.3%), and highest for Romania (32.0%), Poland (30.6%) and Italy (29.4%). The shares of strong free riders are reported in Table 6.

To further explore the relative effects of the two types of free riders, Fig. 3 plots the shares of both weak and strong free riders among all adopters at any given rebate level. The share of total free riders starts at 100% for a zero rebate and drops as higher rebates incentivize additional adopters, while the total number of weak and strong free riders does not vary with the rebate. However, even at a rebate of 1000 euros—which corresponds to half the purchase price of the heating system—the share of free riders remains high, i.e. around or above 50% in all countries. At this rebate level, more than half of the total rebate expenditure (and in

[6] If the cases for which income is missing are dropped, the findings are generally consistent with those reported in Table 5.

[7] As a robustness check, we ran a simple binary response model, where the dependent variable was set to zero for observed weak free riders (i.e. Type 1 in Fig. 1) and to one for incentivized adopters (i.e. Type 2) and non-adopters (i.e. Type 3). Signs and significance of the coefficients are consistent with those reported in Table 5.

[8] In addition to the *all-countries* model presented in Table 5, we ran individual country models. While there is heterogeneity in findings across countries, they are rather consistent. The coefficient associated with *savings* was found to be negative and statistically significant for four countries. For two of the remaining countries the *p*-value was between 0.1 and 0.2, thus providing (at least weak) evidence for internally consistent choices in most countries.

[9] For Italy, the estimated rate is 5.8 percentage points, and thus very close to the 6-percentage point probability increase for an equivalent raise that was found by Alberini and Bigano (2015) for heating systems in Italy.

Table 6
Parameter assumptions for the simulations.

	FR	DE	IT	PL	RO	ES	SE	UK
Sample size[a]	915	634	1089	1311	706	1299	594	948
# of households[b] (×1000)	28,920.4	40,257.8	25,788.6	14,113.4	7469.7	18,376.0	5099.8	28,218.5
Gas price[c] (€/kWh)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
CO_2 factor (kg-CO_2/kWh)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Savings (€)	1000	1000	1000	1000	1000	1000	1000	1000
Share of strong free riders[d] (%)	12.4	19.8	17.9	13.6	40.6	11.1	8.9	14.0

[a] Subsample of homeowners who stated that they did not purchase a new heating system during the past ten years and who live in a dwelling built before the year 2000 (corresponds to N_{sample} in the analytical model)
[b] Eurostat (2016a)
[c] Eurostat (2016b)
[d] Share of strong free riders in the subsample

Germany two-thirds) would go to free riders. Notably, the composition of total free riders differs substantially across countries.

Fig. 3 implies that for most countries the share of weak free riders is greater than the share of strong free riders. In Romania, though, most free riders are strong free riders (see Table 6).[10] As expected, as the rebate increases, total program costs increase, but the share of the rebate expenditures going to free riders decreases.

Our estimates of strong free-ridership are conservative when compared to the expected natural turnover rate. In the survey, we asked households about their intentions to replace their heating systems within the next five years. On average, 12% of all home owners stated an intention to replace (Table 1, row G/row B) and were classified as strong free riders in our analysis. However, 35% said to have replaced their heating systems in the past 10 years (Table 1, (row C − row D) / row C), suggesting an average practical lifetime of 29 years (=10 years/0.35), which is longer than the 22 years generally assumed (e.g. Connolly et al., 2014; Fleiter et al. 2016, p.11). The corresponding expected strong free-rider rate is then 17% (=5 years/29 years).[11]. We argue that our lower percentage of strong free riders may be explained by the fact that households do not commonly anticipate a system breakdown and that many of them would not state an intention to replace a well-functioning system even if the actual end of the technical lifespan is within five years.

3.3.3. CO_2 emissions and cost-effectiveness

For further elaboration, we simulate the effects of the rebate on CO_2 emissions. To do so, we need to make additional assumptions. We standardize as many parameters across countries as possible to isolate the effects of differences in free riding on the cost-effectiveness of the rebates. To calculate the CO_2 emissions per replaced heating system, we first assume that the old and the new systems are gas-fired.[2,12] We then translate the energy cost savings into kWhs saved (i.e. Δe in Eq. (7)) using a price of 0.05 €/kWh.[13] Similarly, employing a CO_2 factor of 0.2 kg/kWh (corresponding to γ in Eq. (7)) then yields the CO_2 savings per euro of energy expenditures saved. For simplicity, we assume a total lifetime *savings* of 1000 euros per adoption of a new gas-fired heating system.[14] Table 6 lists the parameter values used in the subsequent simulations.

To calculate cost-effectiveness, we divide the CO_2 emissions saved by incentivized adopters (i.e. without CO_2 emissions saved by weak or strong free riders) by the rebate expenditures (see Eqs. (7) and (8)). Fig. 4 shows these specific rebate costs as a function of the rebate level for all countries. The dotted line denotes specific costs without considering expenditures for weak or strong free riders (a and $b(0)$ set to 0). Since we assume identical savings, gas prices, and CO_2 factors for all countries, this line is linear and identical across countries. The dashed line captures the specific rebate costs, when expenditures for strong free riders are also accounted for ($a = a$ but $b(0)$ still set to 0). Therefore, the difference between the dashed line and the dotted line reflects additional expenditures for strong free riders. The solid line reflects specific rebate costs when expenditures for both strong and weak free riders are included (constraint on $b(0)$ released). The difference between the solid and the dashed lines corresponds to the additional expenditures for weak free riders. Thus, if weak free riders could be identified and transformed into (non-incentivized) adopters (e.g. via low-cost targeted information programs) and excluded from receiving rebates, then a rebate program would be substantially more cost-effective in all countries, especially in Germany and France.

For a rebate of 1000 euros, the specific rebate costs for most countries are just above 500€ /tCO_2. Fig. 2 suggests that at a rebate of 1000 euros (in most countries) at least half of the subpopulation would agree to the proposed heating system replacement. Due to a high share of strong free riders, the specific rebate costs are particularly high for Romania (even though the mean reservation rebate was low). In comparison, we also note that for some countries (e.g. Sweden), which exhibit relatively high mean reservation rebates, the specific rebate costs may be rather low if the shares for weak and strong free riders in these countries are low.

Fig. 5 displays specific rebate costs as a function of abated emissions for each country. The shapes of the curves and the interpretation of our findings on the impact of weak and strong free riders are analogous to those in Fig. 4. In addition, the differences in the shapes of the curves across countries in Fig. 5 suggest that cooperation among countries to achieve a given aggregate CO_2 emission level could yield reductions in public expenditure. Depending on the aggregate target, it appears preferable to prioritize implementation of the rebate program in the UK, and Poland.[15]

4. Discussion and conclusions

For countries and energy companies to achieve ambitious energy and climate policy targets, it is crucial to account for free riding when assessing the cost-effectiveness of programs (such as rebates incentivizing technology replacement) designed to support customer conversion to energy efficient technologies. Relying on contingent valuation choice experiments carried out through identical representative surveys in

[10] In Romania, there is an ongoing transition in urban areas away from old, inefficient district heating systems to individual gas boilers (NEEAP Romania, 2015, p. 134).

[11] The ratios of the expected replacement shares based on estimated lifespans and the shares of strong free riders among all home owners vary between 1.0 (Romania) and 2.3 (Sweden).

[12] In Poland, coal boilers are the more common replacement type, making the results of the simulations for Poland more conservative. For Sweden, though, electric heat pumps are most common. Thus, results of the simulations for Sweden need to be taken with some caution.

[13] This figure is very close to actual gas prices during the first half of 2016 for six of the eight countries included in this study (Eurostat, 2016b). Only gas prices in Poland (0.032 €/kWh) and Romania (0.018 €/kWh) were substantially lower.

[14] Additional simulations carried out as a sensitivity analysis suggest that using 500 euros for total lifetime *savings* leads to qualitatively very similar findings as using 1000 euros.

[15] At present, no aggregate EU (or national) emission target exists for specific activities such as space heating. So, this finding is only illustrative of the reductions in public expenditures that cooperation across countries might involve.

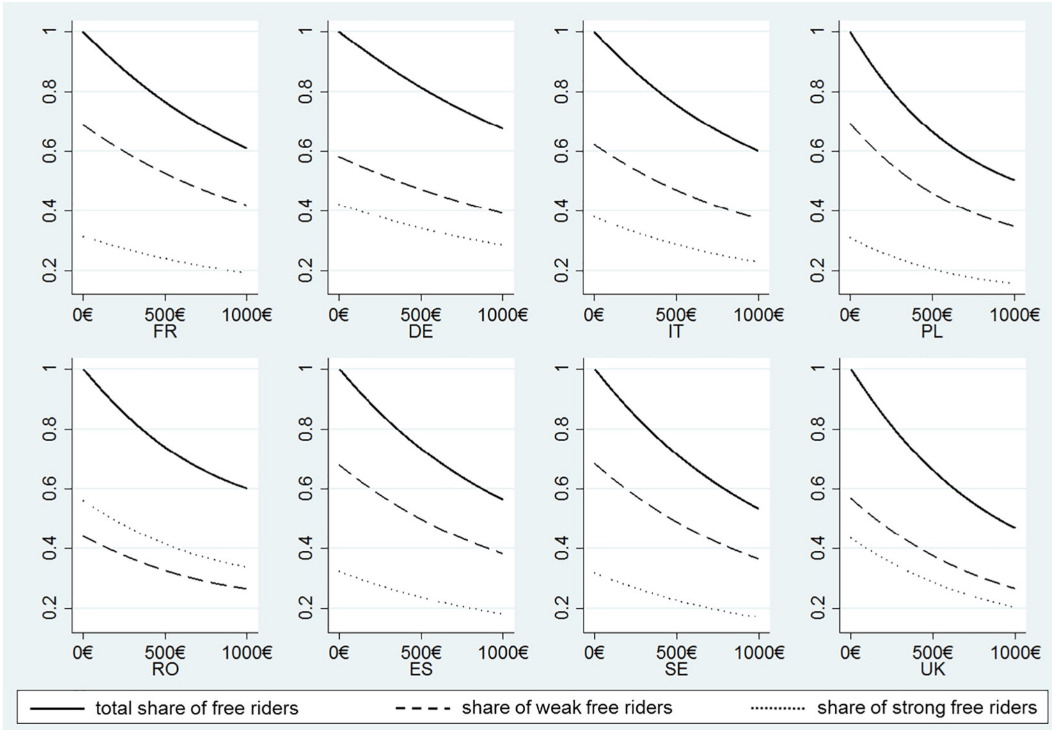

Fig. 3. Shares of free riders as a function of the rebate level.

eight EU Member States, we ex ante assess the effects of free riding on the cost-effectiveness of a rebate program that incentivizes the adoption of energy-efficient heating systems in these countries. Conceptually and empirically, we distinguish between what we name strong and weak free riders: strong free riders are households planning to adopt a new heating system even without any information or rebate program; weak free riders have reservation rebates equal to or less than zero and only need to be offered an attractive technology package to

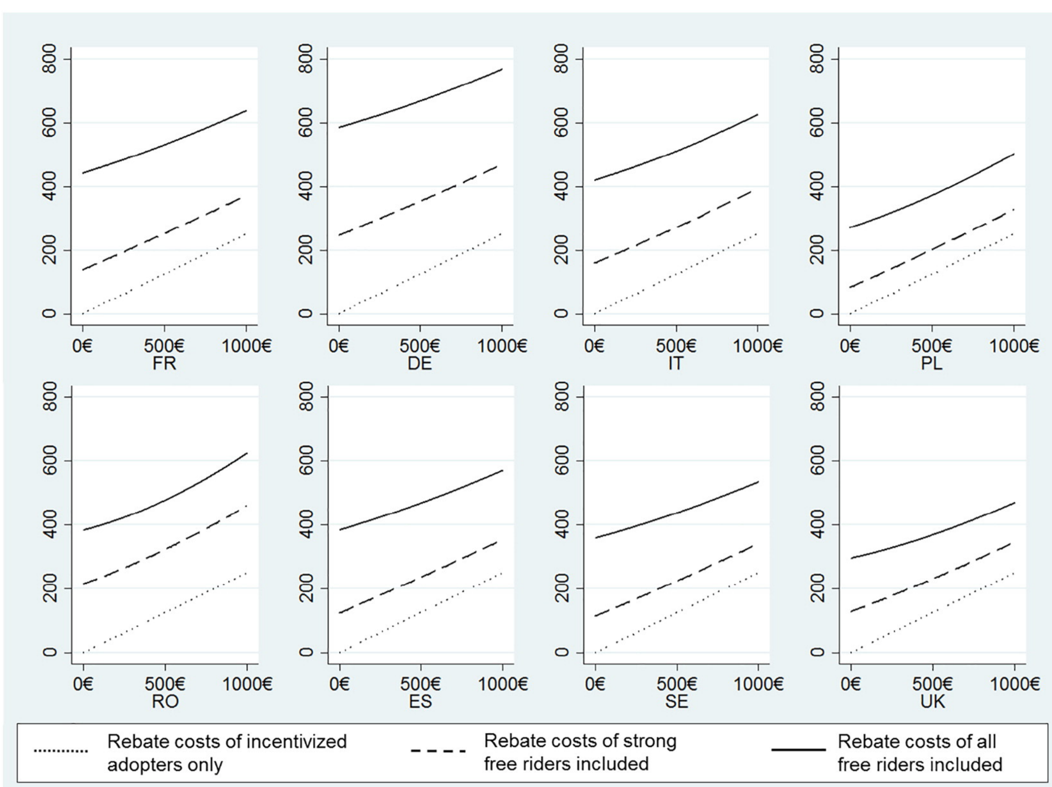

Fig. 4. Specific rebate costs (in €/tCO_2) as a function of the rebate level. Curves correspond to Eq. (8), where the dashed curve is constrained by $b(0) = 0$ and the dotted curve by $a = 0$ and $b(0) = 0$.

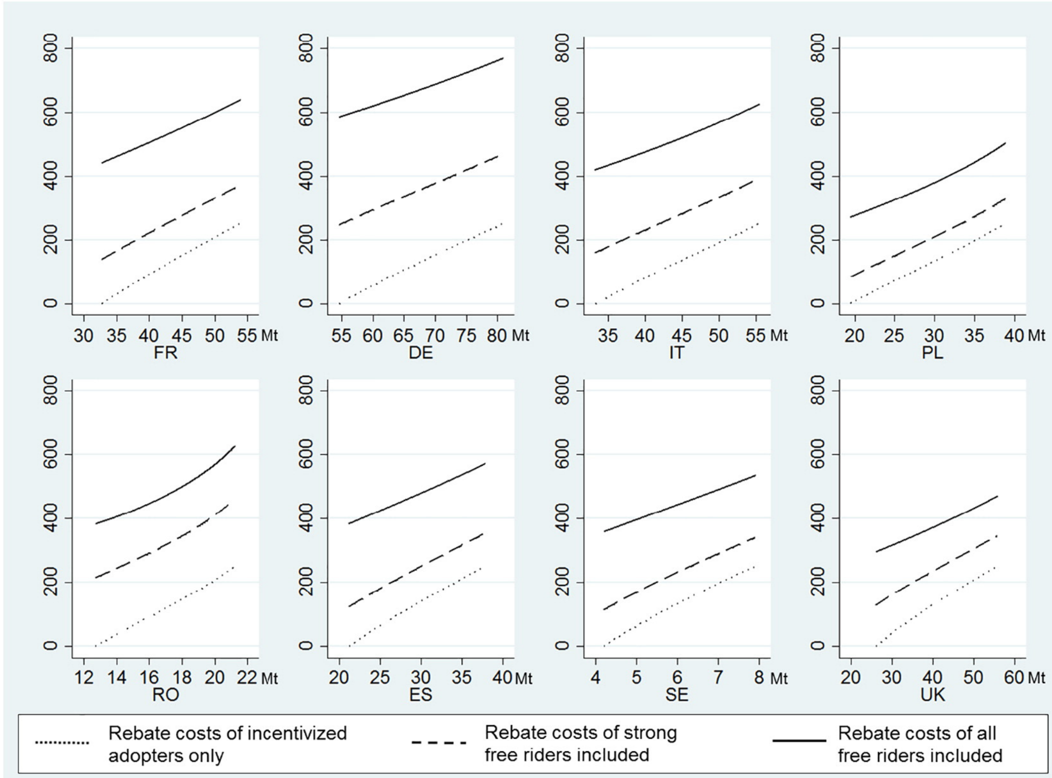

Fig. 5. Specific rebate costs (in €/tCO_2) as a function of abated emissions (in Mt).

decide to adopt (and therefore do not need a rebate program). In contrast, incentivized adopters are those households that only adopt because of the rebate program.

We find that the mean and median reservation rebates for incentivized adopters differ substantially across countries. On average (across countries), this rebate corresponds to approximately 40% of the heating system's purchase price of 2000 euros, suggesting a generally high opportunity cost for the premature replacement of a heating system. The reservation rebate and weak free-ridership vary substantially across socio-economic groups. We find that the reservation rebate correlates positively with income and negatively with willingness to wait, willingness to take risks, and environmental identity. Hence, predicted weak free-ridership decreases with increasing income and increases with patience, risk taking, and environmental identity.

Further, our simulation results suggest that the propensity to adopt a new heating system varies considerably across countries. Raising the rebate by a given amount would be most effective for increasing adoption rates in Romania and Poland, and least effective in Germany and Sweden. At a rebate level of 1000 euros, which corresponds to half the purchase price of the hypothetical heating system, the share of free riders is estimated at around or above 50% for most countries, up to two-thirds for Germany. The decomposition of total free riders, however, differs across countries. We find that for most countries, the share of weak free riders is higher than the share of strong free riders. In general, our ex ante estimates of free-ridership, based on hypothetical technology and incentive offerings, are broadly consistent with the ex post results in the literature on free-ridership within the context of residential energy efficiency improvements, which tend to find free-rider shares of 50% or more.

Our analyses provide some guidance for policy making. First, simulation results imply that for a rebate of 1000 euros, the specific rebate costs for most countries exceed 500 €/tCO_2. Thus, the costs of subsidizing premature heating system replacement as a CO_2 emissions reduction instrument compare to high estimates of the social cost of carbon only (van den Bergh and Botzen, 2014). In addition to the high opportunity costs associated with premature technology replacement, this figure also reflects high shares of strong and weak free riders. Due to a large share of free riders, the specific costs are particularly high for Germany. In contrast, despite an above-average mean reservation rebate, specific rebate costs are relatively low in the UK, owing to its lower share of free riders.

Second, rebates for heating system upgrades appear to be an effective means for governments or energy companies to reach energy and emission targets. The European Union (EU) for example, has set a 20% energy savings target by 2020 in the Energy Efficiency Directive (EED) (2012/27/EU). The EED further requires Member States to lower annual energy sales to final customers by 1.5% each year until 2020. Member States may pass on this responsibility to energy retail companies and/or take policy measures themselves. The European Commission “Winter Package” proposal for an updated EED (COM (2016)/761 final) includes a new 30% energy savings target for 2030 and suggests continuing this commitment to year over year improvement through 2030 and beyond. While effective, our findings further suggest that such rebate programs would be rather costly, because of high shares of free riders.

Third, substantial differences in the shapes of the specific rebate cost curves illustrate that if countries were to achieve a common CO_2 emission reduction target (as in the EU for example), coordinated measures (here: rebates) would yield sizeable reductions in public expenditure.

Fourth, our findings on weak free-ridership attest to the role of attention-getting efforts in increasing program participation (Stern et al., 1986). While a combination of policies may do more for adoption than a single policy, the cost-effectiveness of a non-discriminatory subsidy policy suffers from a parallel instrument's effectiveness. Our results suggest that in most countries (particularly in Germany and France), rebate expenditures would be much lower if low-cost programs - involving communication and information for example - could turn weak free riders into (non-incentivized) adopters.

Thus, rather than implementing rebate and information programs simultaneously, these programs should be introduced sequentially: first information programs to address the weak free riders by helping to overcome information-related barriers, and then rebate programs to reach those households that require financial incentives to prematurely replace their heating system. Of course, a sequential approach raises fairness and equity questions. For example, policy makers would have to announce the rebate program only after the information program had been implemented.

Finally, we want to point out some limitations of our study. First, our findings rely on stated rather than observed behavior. The hypothetical nature of contingent valuation, however, is the price paid for ex ante empirics. As argued by Alberini and Bigano (2015, p. 78), the hypothetical bias associated with stated preferences experiments is likely to be small compared to a potential free-rider bias. Second, heating system technology varies widely across countries; the simulations may be realistic for most countries but probably less so in countries where natural gas boilers are not common, such as in Poland and Sweden, or where gas expenditures are very low (Romania). Third, we ignored program administration costs (Eto et al., 2000) and did not account for rebound effects (e.g. Sorrell and Dimitropoulos, 2008), which can lead to negative absolute savings in appliance subsidy programs (Galarraga et al., 2013). Finally, the choice experiment setting eliminates the reality of uncertainty about future cost savings (Farsi, 2010) and does not capture the extent to which respondents account for additional, 'hidden' costs (e.g. transaction costs) when taking the survey. Grösche and Vance (2009) showed how such hidden costs may reduce free-ridership. Despite these limitations, our proposed method enables us to disentangle ex ante the effects of providing information on costs and benefits from the effects of monetary incentives used by support programs for energy efficient technology upgrades.

Acknowledgement

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Annex I. Description of scales used to elicit personal and attitudinal traits

Willingness to wait and to take risks

We measure time and risk preferences on one-item scales validated by Falk et al. (2016) and Dohmen et al. (2010, 2011).

Respondents were asked to rate the following items on a scale: from 1 "Not at all willing" to 5 "Very willing."

1. How willing are you to give up something that is beneficial for you today in order to benefit more from that in the future?
2. In general, how willing are you to take risks?

To construct *WTWait* and *WTRisk* we calculated the z-score on each scale.

Cognitive Reflection Test (CRT)

Cognitive reflection tests were designed to assess individual ability to suppress an intuitive and spontaneous wrong answer in favor of a correct answer (Frederick, 2005). To measure cognitive reflection, we use the following items:

CRT1: A bat and a ball cost 1.10€ in total. The bat costs 1.00€ more than the ball. How much does the ball cost?
CRT2: If it takes 5 machines 5 min to make 5 widgets, how long would it take 100 machines to make 100 widgets?
CRT3: In a lake, there is a patch of lily pads. Every day, the patch doubles in size. It takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake?

To construct *CRT*, we first calculated the number of correct answers to the three items and then calculated the z-score.

Environmental identity

We use an adapted version of the four-item environmental identity scale developed by Whitmarsh and O'Neill (2010). Respondents were asked to rate the following items on a scale from 1 "Strongly disagree" to 5 "Strongly agree."

1. To save energy is an important part of who I am.
2. I think of myself as an energy conscious person.
3. I think of myself as someone who is very concerned with environmental issues.
4. Being environmentally friendly is an important part of who I am.

To construct *ENV_ID*, we took the unweighted average of the z-scores of the four items.

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