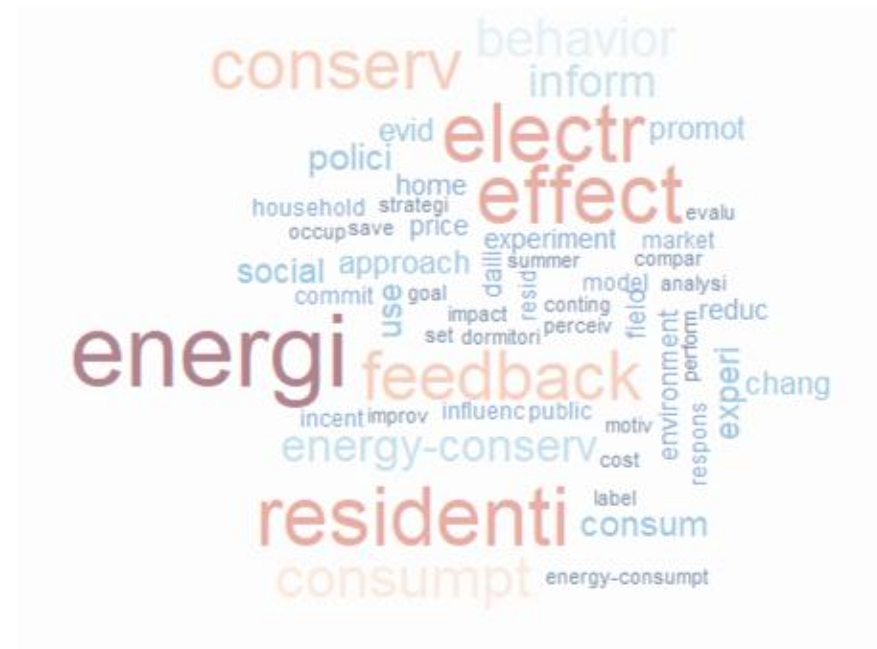


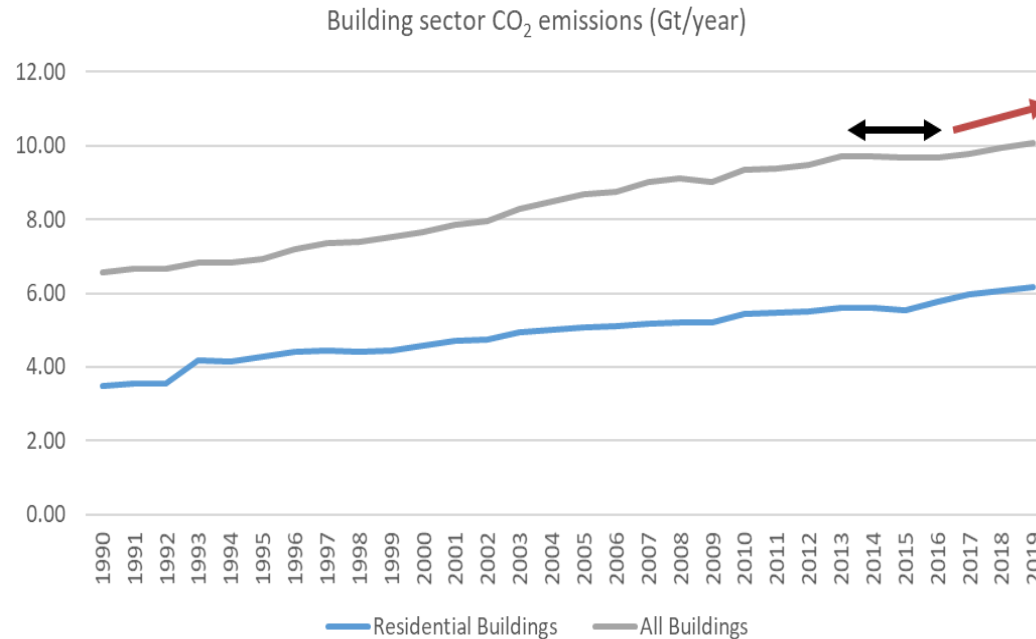
Meta-analysis to assess the role of behavioral change in reducing energy consumption and emissions in residential buildings

Tarun Khanna, Giovanni Baiocchi, Max Callaghan, Felix Creutzig, Horia Guias, Neal R Haddaway, Lion Hirth, Aneeqe Javaid, Nicolas Koch, Sonja Laukemper, Andreas Löschel, Maria Del Mar Zamora, Jan C Minx



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Household emissions in residential buildings – important source of emissions



- Globally, buildings account for 28% of carbon emissions (direct + indirect emissions)
- After plateauing between 2013-16, building emissions are rising again
- Demand side approaches are a necessary to de-risk supply decarbonization pathways—excessive reliance on supply side measures

Behavioural change to reduce energy demand

 <p>Monetary Incentives</p> <ul style="list-style-type: none">Time of Use PricingReal-time PricingCritical Peak PricingSeasonal PricingRewards/ Rebates	 <p>Feedback</p> <ul style="list-style-type: none">HistoricalDescriptiveInjunctiveIn-home Displays
	 <p>Social Comparison / Norms</p> <ul style="list-style-type: none">Home Energy ReportsNormative Feedback
 <p>Information</p> <ul style="list-style-type: none">Home AuditsTipsReminders	 <p>Motivation</p> <ul style="list-style-type: none">Goal SettingCommitment DevicesGamification

Well established and mature literature but lack of systematic evidence synthesis that can inform climate change mitigation discussions

Research Questions

1. By how much can monetary incentives and behavioural interventions reduce energy consumption of households in residential buildings? **(average treatment effect of interventions)**
2. Which interventions are most effective? Under what conditions? **(account for heterogeneity in treatment effect across studies)**
3. By how much can CO₂ emissions be reduced using such interventions? **(mitigation potential)**

Comprehensive, machine learning assisted review of scientific literature (>60k articles)

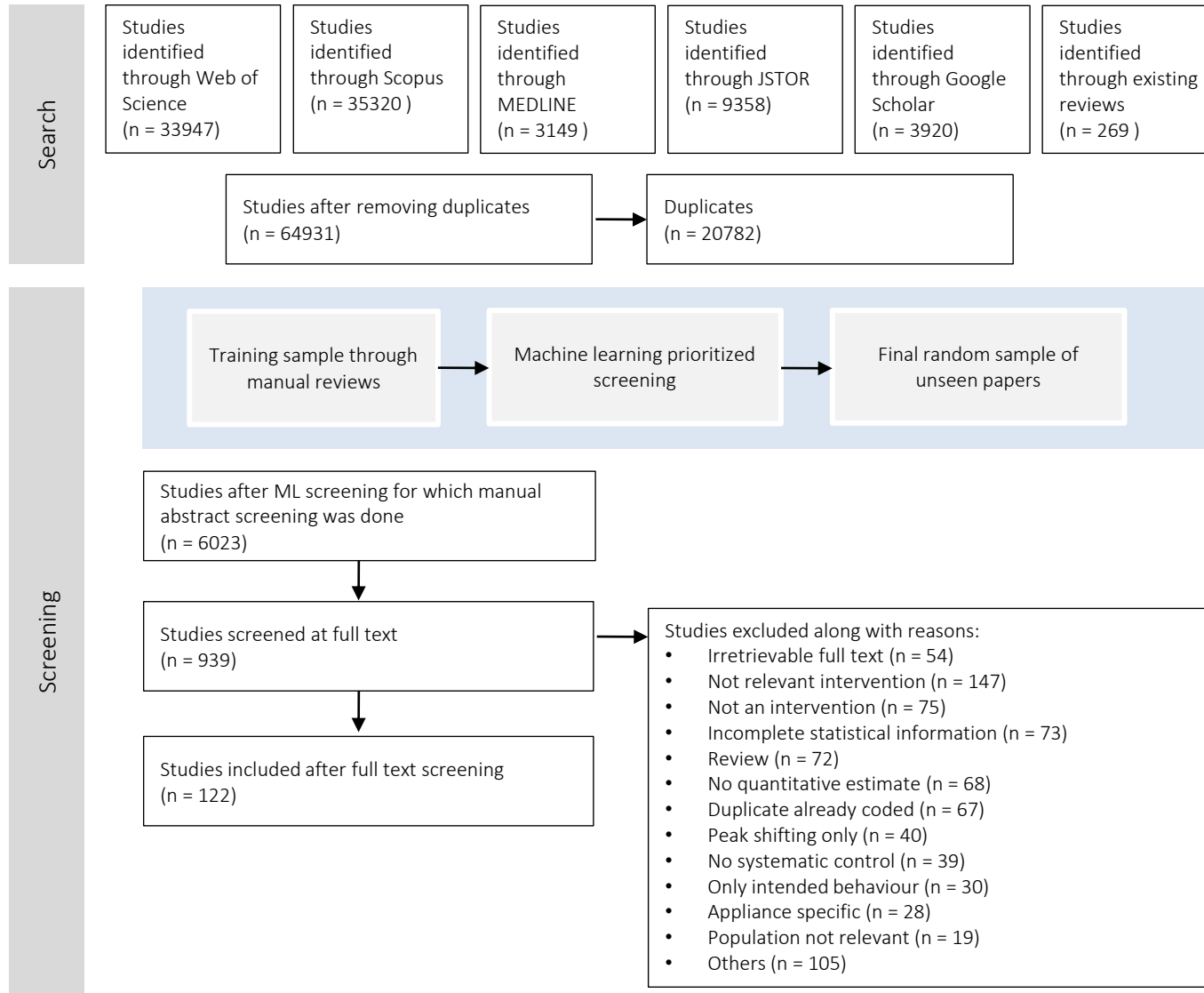
Meta-regression of results of 122 primary studies

Sample represents evidence from > 1.1 million households in 25 countries

Assess causes of heterogeneity and calculate potential emissions reductions

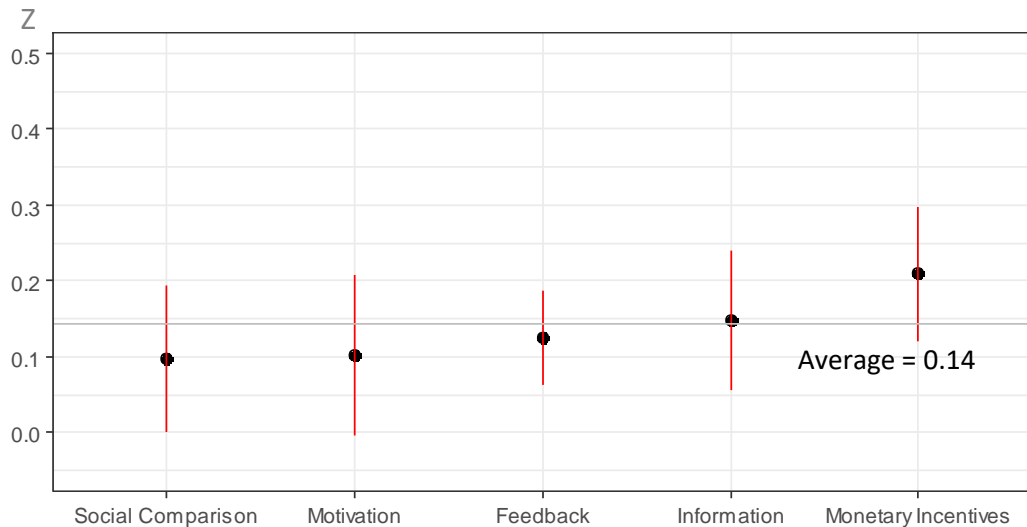
- Bring together insights from economics and psychology
- Better understand the impact of various interventions in relation with each other
- Calculate a carbon mitigation wedge

Systematic review and meta analysis



Interventions induce energy reductions

	ATE	95% CI	95% PI
Random effects model DL estimator	0.10	0.08, 0.11	0.02, 0.18
Random effects model with REML estimator	0.15	0.13, 0.17	-0.23, 0.53
Multilevel model with REML estimator	0.15	0.12, 0.18	-0.22, 0.52
Multilevel model with REML estimator (excl. studies without randomization)	0.14	0.11, 0.18	-0.20, 0.49

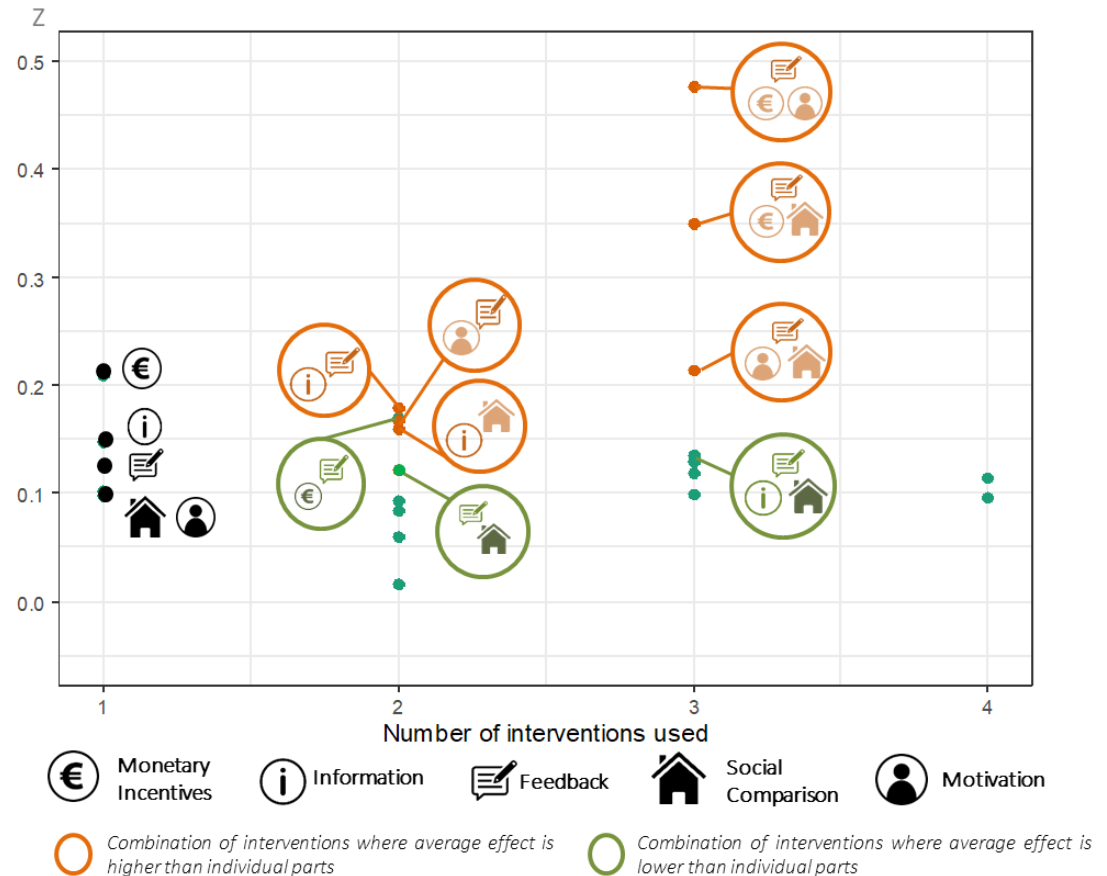


*Dependent variable in our analysis is Fisher's Z that indicates the strength of correlation between the dependent and independent variable
 $Z > 0$: reduction in energy demand*

- The effect is moderate and statistically significant across model specifications
- There is high degree of heterogeneity in the aggregate effect sizes
- The average effect for the subsets of papers that studied only monetary incentives seems to be higher than those that studied only information, feedback, social comparison, and motivation

Combinations of interventions better, but ...

- Certain combination of interventions perform better than their individual parts.
- For example, the average aggregate effect for studies that combine feedback, social comparison and monetary interventions is even higher (0.35) and is higher than average aggregate effect size for feedback, monetary interventions, social comparison individually.
- Effect size of the combination of feedback and monetary incentives (0.17) is lower than the effect size of monetary incentives (0.21)



Heterogeneity in effects

Investigate heterogeneity by added moderator variables to the meta-regression models that represent either differences in the effectiveness of these interventions based on the context or elements of study design.

Regional variation:

- Compared to the studies from the United States, studies from Asia report higher effects, especially those that employ monetary incentives or motivation.
- Studies from continental Europe seemed to report marginally larger effects but the difference is not statistically significant.

Time trends:

- Effect reported by newer studies is lower. The coefficient of the variable study year is negative and statistically significant in almost all model specifications.
- Studies with longer treatment duration report smaller effects.
 - > Studies with treatment duration of more than 100 weeks find negligible effects. Need more long term trials.

Heterogeneity in effects

Study design:

- The control-treatment and difference in difference DID designs in our data measure a lower reduction in energy consumption.
-> Pre post studies are fairly common in this field of research with about 16% of our sample coming from studies with pre post design, even in studies done more recently.

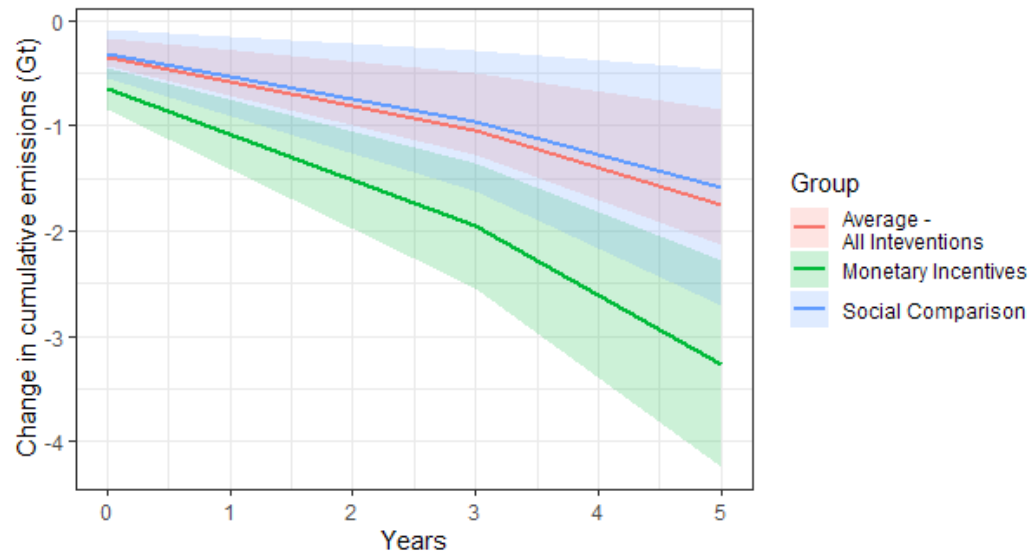
Household selection:

- *Randomisation*: The coefficient for randomisation is not consistent in sign nor is it statistically robust.
- *Opt-in*: small positive bias, especially for monetary incentives which have the highest effects

Study level controls:

- *Weather*: studies that control for weather report lower effects
- *Residence type*: Studies that control for characteristics of the house (size, appliances) tend to find a smaller effects
- *Demographics*: studies that controlled for demographic differences between the households find higher effects

Mitigation potential



- Average emissions reductions of 0.35 Gt CO₂/year. Very modest compared to the approximately 5.5 Gt CO₂ of emissions from residential buildings in 2018
- Higher potential in specific contexts—combinations of interventions, marginal reductions in coal power use, limit demand growth in Asia & Africa
- Expected that the impact is short lived
- Research on interventions related household behavior around upgradation of heating/cooling, insulation and other structural changes needed

Appendix

Interventions for reducing energy demand

Monetary Incentives

Author: Faruqui et.al 2010, Colorado Xcel Energy TOU pilot
Aim: Test impact of TOU and CPP rates
Period: July 15, 2006 to July 15, 2007
Treatment population: 2,900 residential customers opt in
Effect: 5-10% reduction in peak and 0-3% reduction in off-peak consumption

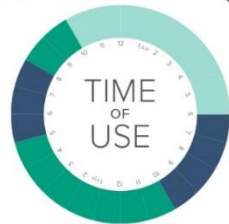
MAY 1–OCTOBER 31
All days, unless noted below



On-peak M–F 3PM–8PM
Mid-peak M–F 6AM–3PM, All 10PM–6AM
Off-peak All 7PM–10PM

*Mid-peak Saturday is 6AM–10PM
**On-peak Sunday & some holidays is 6AM–10PM

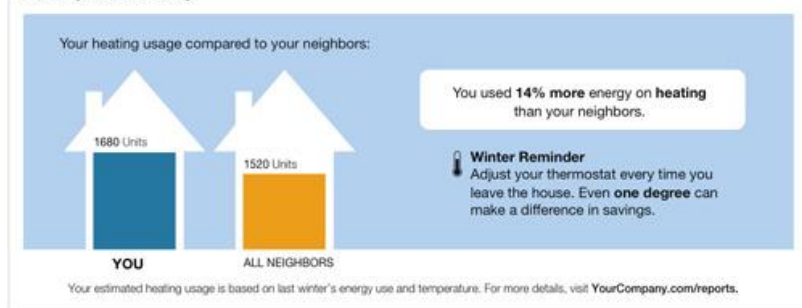
NOVEMBER 1–APRIL 30
All days, unless noted below



On-peak M–F 6AM–10AM, 5PM–8PM
Mid-peak M–F 10AM–5PM, 8PM–10PM
Off-peak All 10PM–6AM

*Mid-peak Saturday is 6AM–10PM
**On-peak Sunday & some holidays is 6AM–10PM

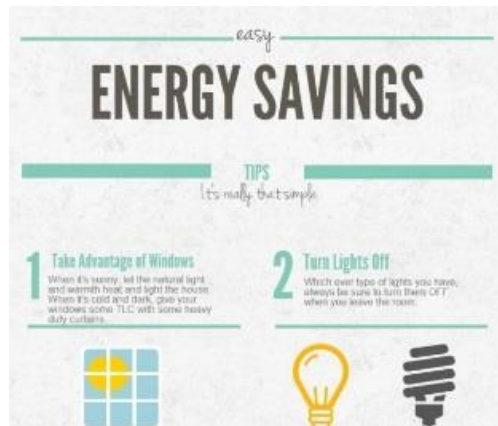
Spotlight on Heating



Social Comparison

Author: Alcott, 2009, OPOWER Pilot
Aim: Impact of Home Energy Report
Period: January 2008 and August 2009
Treatment population: 78,492 households randomized into treatment and control
Effect: 1.5-2% reduction in electricity consumption

Interventions for reducing energy demand



Information

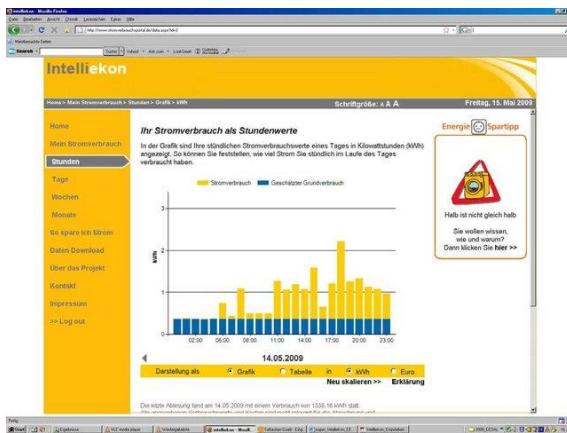
Author: Casado et. al 2017

Aim: Impact of public awareness advertising campaigns

Period: February to June 2014

Treatment population: 321 households randomized into treatment and control

Effect: messages on energy efficiency combining specific behaviour guidelines and economic benefits are effective



Feedback

Author: Schleich et al. 2013

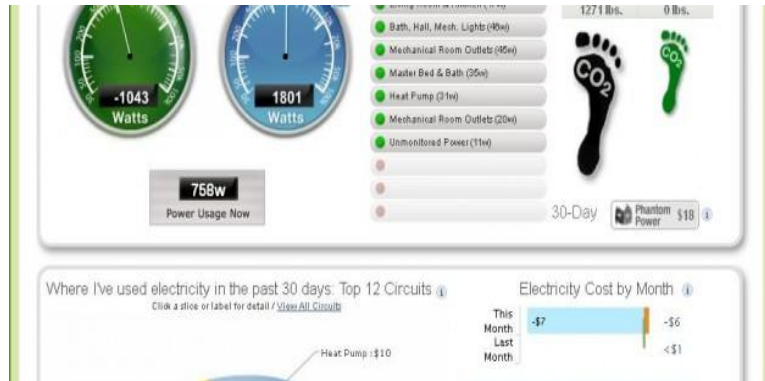
Aim: Impact of feedback on electricity consumption

Period: December 2009 to November 2010

Treatment population: 1500 households in Linz, Austria

Effect: 4.5% reduction in consumption for the average household

Interventions for reducing energy demand



Motivation

Author: Castri et. al 2016

Aim: Gamification to reduce demand

Period: February and May 2016

Treatment population: 108 volunteering households

Effect: 3-6% reduction in electricity consumption

Existing systematic reviews

Delmas et. al (2013)

- Information provision
- Feedback (own use)
- Pecuniary strategies
 - Rewards/ rebates
 - Price signals
 - Monetary information
- Norms or social comparison
- 59 studies; excludes non-field experiments

Karlin and Zinger (2015)

- Frequency of feedback
- Medium of communication
- Measurement (in kWh or money)
- Combination with other incentives
- Social comparison
- Granularity
- Duration
- 42 studies; limited interventions covered

Nisa et. Al (2019)

- Interventions in all behaviors of households relating to climate mitigation
- Covers a subset on feedback, information
- 47 studies, excludes pricing

Andor and Fels (2018)

- Social comparison
- Commitment devices and goal setting
- Labeling
- 44 studies; limited interventions covered

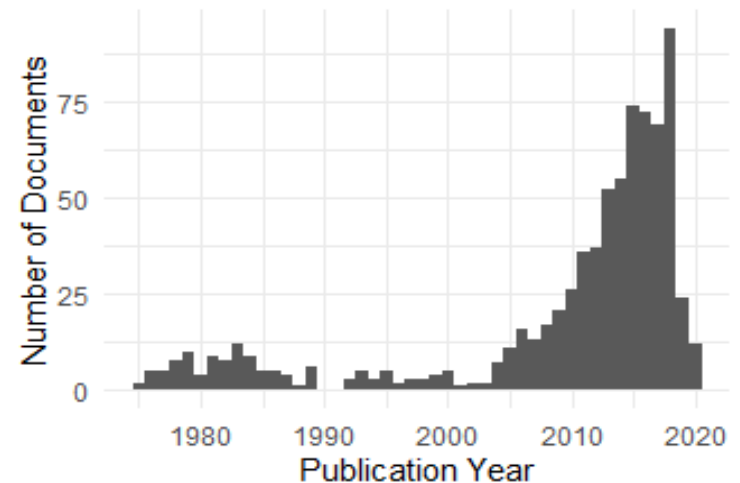
Buckley (2020)

- Information, Behavioural and Monetary incentives
- 52 studies; excludes studies before 2005, non-field experiments, developing countries

Gaps in existing assessments

- Existing research looks are subsets of behavioral interventions – need for comprehensive, interdisciplinary review
- Captures the complete literature from 1970 to 2020
- Only one partial assessment of mitigation potential of behavioral interventions (Andor et al. (2017) for HER in Germany and the US)

Literature related to Household Energy Interventions

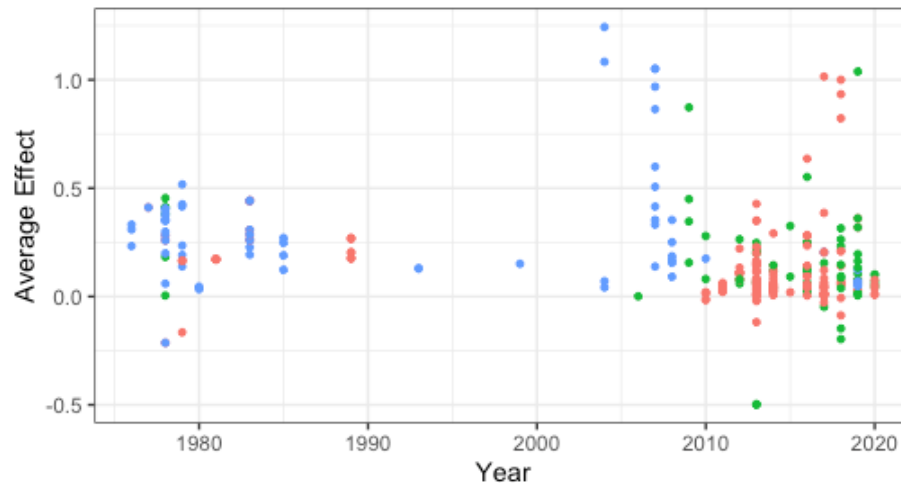
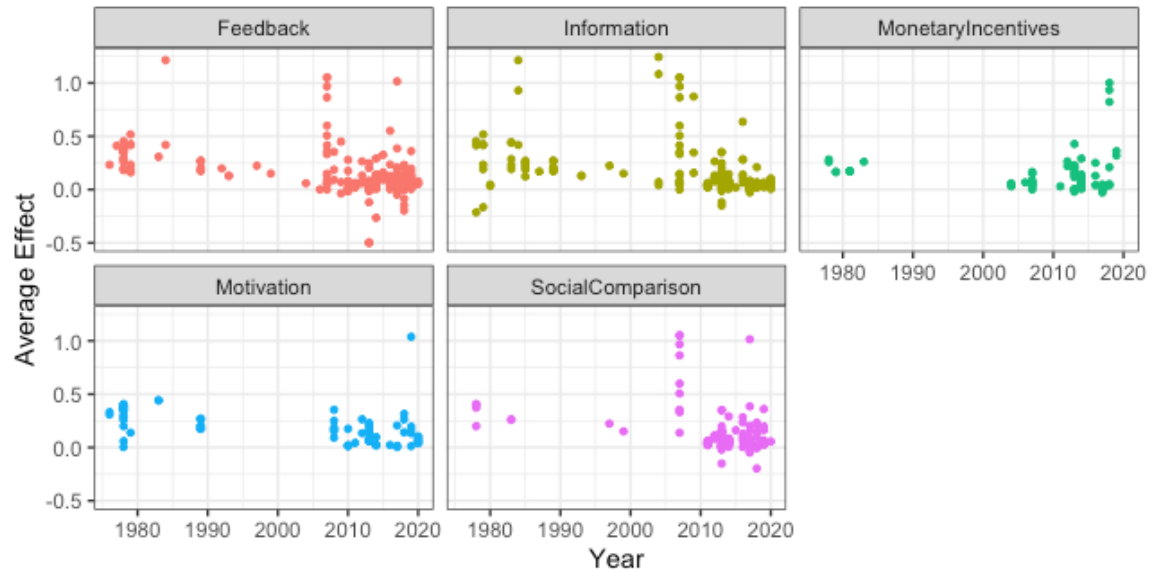


Snapshot of the sample

Total number of primary studies	122
Total number of effect sizes (estimates)	360
Time period	1976-2020
Number of countries	25
Number of households in the underlying studies	1.1 million
Mean annual electricity consumption per household	7439 (8845) kWh
Mean duration of the experiment	21.5 (26.8) weeks

Snapshot of the sample

- Research was fashionable in the 70s and 80s and has again gained momentum since 2000
- Feedback and information have been consistently well studied. The literature on monetary interventions is relatively recent
- This was particularly popular in psychology earlier but now more papers are being published in economics and engineering



Accounting for heterogeneity in effect sizes

- Meta regression model to account for heterogeneity in effect sizes that is not explained by statistical variance

$$Z_i = b_0 + b_1 X_1 + b_2 X_2 + \tau^2 + e_i$$

Effect size Moderator Variable Variance in effect size + sampling variance

- The moderator variables represent factors that genuinely affect the magnitude of effect size in the population, e.g. type of intervention
- Or they could represent heterogeneity caused by design of the study, e.g. the statistical model used, quality of study, control variables in the underlying study

Regression results

	All	Feedback	Information	Monetary	Motivation	Social
				Incentives		Comparison
Intercept	5.38*	7.38**	3.31	1.26	2.56	7.12
Study Design DID	-0.14***	-0.25***	-0.19**	-0.08	0.20**	-0.31***
Study Design Control -treatment	-0.09*	-0.24***	-0.16**	-0.03	0.19*	-0.32***
Stats Method Means Differences	0.11**	0.10**	0.20**	-0.02	0.00	0.22**
Stats Method Panel Effects	0.01	-0.01	-0.01	0.14	-0.03	-0.01
Weather	-0.01	0.01	0.00	-0.19*	0.13	0.06
Household Type	0.00	0.03	0.05	0.30	-0.05	0.02
Residence Type	-0.03	-0.03	-0.05	-0.20	0.01	-0.02
Opted-In Yes	0.04	0.01	0.03	0.17**	-0.10	-0.09
Randomization Yes	0.03	0.10*	0.06	-0.05	0.05	-0.29
Intervention Treatment Period	-0.00*	-0.00**	-0.00	-0.00**	-0.00	-0.00
Region Asia	0.16***	0.02	-0.00	0.16	0.01	0.09
Region United Kingdom	0.03	-0.06	0.03	-0.19	-0.22*	0.07
Region Continental Europe	0.02	0.01	0.04	0.13	-0.04	-0.08
Region Others	0.03	-0.01	0.08	-0.12	0.06	-0.06
Study Year	-0.00*	-0.00**	-0.00	-0.00	-0.00	-0.00
In home display		-0.04				
Rewards				-0.03		
Commitment strategies					0.25**	
Gamification					0.08*	
No. of Effects	317.00	192.00	149.00	71.00	68.00	111.00
I2	99.43	99.14	99.58	97.34	26.46	99.39
R2	28.73	57.05	36.91	41.38	93.17	57.85

*** p < 0.001; ** p < 0.01; * p < 0.05