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From natural gas to electric appliances: Energy use and emissions implications in Australian homes

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Mara Hammerle
Crawford School of Public Policy, Australian National University

Paul J. Burke
Crawford School of Public Policy, Australian National University

Abstract

Does variation in household vulnerability influence the effects of switching to new energy-efficient electrical appliances in the home? Using the Australian Capital Territory (ACT) Energy Efficiency Improvement Scheme (EEIS) as a case study, this paper examines impacts on energy consumption and greenhouse gas emissions from replacing natural gas heaters and hot water systems with more energy-efficient electric alternatives. To do so we use quarterly billing data over 2015–2020 for a sample of residential customers of the ACT's largest energy retailer, ActewAGL. Based on fixed effects panel regressions, we find that the electric replacements led to large decreases in residential natural gas consumption and smaller increases in consumption of electricity from the grid in energy content terms. Reductions in natural gas use from switching to electric hot water heaters were particularly large for the more vulnerable households in the scheme. The emissions effects depend on the emissions factor applied for grid electricity and underline the key role that residential electrification can play in decarbonization efforts if electricity is from low-emission sources.

Keywords:
energy efficiency; household behaviour; distributional impacts; energy efficiency incentives; energy consumption; greenhouse gas emissions

JEL classification:
Q48, Q49, R20, R28

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Address for correspondence:
Mara Hammerle
Crawford School of Public Policy
Email: mara.hammerle@anu.edu.au

1. Introduction

Reducing greenhouse gas emissions from the residential sector involves efforts to improve energy efficiency and electrify energy services such as heating and cooling (Fournier et al. 2020). If electricity emerges as the main energy carrier and electricity generation becomes increasingly decarbonized, this offers a pathway to sizeable emissions reductions (Dennis 2015). Yet the overall challenge of reducing residential emissions is large, and potentially complicated by behavioral responses such as rebound effects. Few studies have empirically investigated the energy use and greenhouse gas emissions implications of interventions that seek to electrify the residential sector.

The Australian Capital Territory (ACT), where Canberra is located, has a goal to substantially reduce natural gas use as part of a plan to cut emissions to net zero by 2045 (ACT Government 2019a). A key intervention has been in the form of the Energy Efficiency Improvement Scheme (EEIS), which aims to reduce greenhouse gas emissions and energy consumption by households and small- to medium-sized businesses. To meet its obligations under the EEIS, the ACT's largest energy retailer, ActewAGL, has offered discounts for energy-efficient electric appliance upgrades to households across the territory. Households who live in public housing have received these appliances cost-free. While large reductions in energy use and greenhouse gas emissions have been modelled using engineering-style approaches (Jacobs Group 2014; Point Advisory 2018), residence-level effects have yet to be estimated using observed billing data.

In this paper we use billing data for over 14,000 ActewAGL households in the ACT over 2015–2020 and pose two research questions:

1) What are the impacts of replacing natural gas heaters and hot water systems with more energy-efficient electric alternatives on residential energy use and related greenhouse gas emissions?
2) Does heterogeneity in household vulnerability influence these impacts?

We compare outcomes for both priority and non-priority households. Under the EEIS, the "priority" group classification aims to include households with low levels of income who are likely to be able to benefit substantially from energy efficiency improvements but are most in need of financial assistance to be able to do so (ACT Government 2019b). Examples include households who receive an energy concession from the ACT Government or access a financial hardship program of an energy retailer; households who live in public housing; and households who have at least one member who holds a Commonwealth low-income health care card, disability support pension, or pensioner concession card (ACT Government 2019b). There are also several other categories of "priority" households. Non-priority households are other households who participated in the EEIS. Our dataset also includes data for control households who did not participate in the EEIS.

Many of the priority households under the EEIS are vulnerable to experiencing energy poverty and to facing difficulties in paying their energy bills. Some experience socioeconomic disadvantage for reasons including that they are asset and/or income poor. Household members who are older or are chronically ill tend to have higher per-capita requirements for residential energy for reasons including that they may be home more often, may be less able to biologically cope with extremes in temperature, and may need to use energy-consuming health equipment (Büchs et al. 2018; Liao and Chang 2002; White and Sintov 2020). Aged pensioners are less likely than younger socio-economically disadvantaged households to be hardship customers in Australia (Simshauser and Nelson 2014).[1] However the energy expenditures of pensioners tend to be high relative to their incomes (Chan 2016), and pensioners are more likely to experience energy poverty than other retirees (Fry, Farrell, and Temple 2022).

The study finds evidence of large reductions in natural gas consumption and smaller increases in grid electricity consumption (measured in megajoules (MJ)) as a result of switching to new energy-efficient electric appliances under the EEIS. The net effect is an average decline in residential energy consumption, especially after the installation of a new reverse-cycle electric air-conditioning system (RCAC). This is of interest because the RCACs offered households both cooling and heating opportunities, whereas the replaced gas heaters provided heating only. Compared to non-priority households, priority households experienced larger percentage declines in total energy consumption as a result of installing an RCAC and larger total (measured in MJ) declines after installing a new electric hot water system. We also identify greenhouse gas emission reductions as a result of the EEIS, although the extent to which these have occurred depend on the emissions factor used for grid electricity.

[1] Hardship customers are defined as those households who face difficulties paying their energy bills due to financial hardship (Australian Energy Regulator 2019).

This paper shares similarities with studies by Davis et al. (2014) and McCoy and Kotsch (2021). Using information on measures of income or deprivation at the county or area level for Mexico and the United Kingdom, respectively, they found smaller reductions in residential energy consumption due to energy-efficiency upgrades in more socioeconomically-disadvantaged localities. In contrast, we use household-level measures of vulnerability. Our approach avoids potential issues from aggregation bias.

The paper proceeds as follows. Section 2 provides background about the EEIS and the ActewAGL discounts. A literature review follows in section 3, with a focus on the importance of household vulnerability for responses to energy efficiency improvements. Sections 4 and 5 describe the data and methods. Section 6 provides the results. Section 7 discusses the implications and concludes.

2. The EEIS

The ACT has been a leader among Australian states and territories in action to address climate change. Among its initiatives, in 2013 the ACT Government introduced an EEIS that obligates electricity retailers to achieve energy savings and greenhouse gas emission reductions among residences and small-to-medium businesses. Large (Tier 1) retailers must deliver approved energy saving initiatives, while smaller retailers can deliver their own initiatives or contribute funding for initiatives. The EEIS requires Tier 1 retailers to achieve a certain percentage of their obligated energy savings in the residences of priority households: 20 percent over 2017–2019 and then 30 percent from 2020 (ACT Legislation Register 2012). The EEIS continues to be in operation.

ActewAGL is the only Tier 1 electricity retailer in the ACT, with a residential market share of approximately 81 percent for both electricity and natural gas as of late 2019 (Australian Energy Market Commission 2020).[2] As part of satisfying its EEIS obligations, the retailer has offered household discounts on energy-efficient reverse-cycle electric air-conditioning systems and hot water systems. All ActewAGL residential customers are eligible if they have an active electricity account, live in the ACT, and have an existing heating or hot water system. There are no income or wealth tests for eligibility. To participate, households must register their interest with an ActewAGL-approved appliance installer and, if eligible, make an installation appointment.

[2] Tier 1 energy retailers are those with at least 5,000 customers in the ACT and that sell at least 500,000 MWh of electricity per year in the territory (ACT Legislation Register 2012).

As highlighted in Table 1, there have been two main types of appliance upgrades under the EEIS. First, households have been able to receive a discount on a new electric hot water system. To be eligible, households must have an existing natural gas hot water system (either storage or instantaneous) or an electric resistance hot water system and switch this out under the scheme. Second, households have been able to replace their existing natural gas heater with a new electric RCAC. The new RCACs can provide both heating and cooling services, and include both ducted and non-ducted models. Households can receive a maximum of two discounts: a maximum of one for a new RCAC and a maximum of one for a new electric hot water system.

Table 1: ActewAGL incentives for energy efficiency upgrades

Existing system	New system	Upfront discount (on costs of installation) (A$)		Credit on electricity account (per quarter, over two years, A$)	
		Priority	Non-priority	Priority	Non-priority
Ducted natural gas heater	Eligible ducted electric reverse-cycle air-conditioning system	2,000	2,000	375	250
Natural gas room heater	Eligible electric reverse-cycle air-conditioning system	1,000	1,000	190	125
Electric resistance room heater	Eligible electric reverse-cycle air-conditioning system	-	-	-	-
Natural gas hot water system (storage or instantaneous)	Eligible electric hot water heat pump	1,200	750	-	-
Electric resistance hot water system	Eligible electric hot water heat pump	1,200	750	-	-

Notes: The above is for quotes accepted during 8 July 2019–20 February 2021. The electric resistance room heater upgrades were completed under a special program for public housing tenants only at zero cost to the customer. Public housing tenants do not receive cash discounts or credits, as the installations are not paid for by the tenants themselves. – indicates "not applicable".

The available discounts have differed by appliance and in some cases have been larger for those identified as priority households under the EEIS. There are two types of incentive. The first is an upfront discount applied at time of sale. This has been higher for new RCACs than for hot water system replacements. Households who upgrade their heating systems also receive credits on their electricity accounts over a period of two years. ActewAGL applies these credits quarterly, the typical billing frequency for residential customers in the ACT.

Most of the priority household beneficiaries under the EEIS have been households in public housing.[3] These households do not own or pay for their heating and hot water systems and therefore have not received the direct financial incentives. Households in public housing may either be referred to ActewAGL for the EEIS by Housing ACT or can ask their Housing Manager for permission to participate. They may also be referred by other entities such as St Vincent de Paul, a non-governmental organization. The main eligibility requirements imposed by the public housing provider, Housing ACT, are that the dwellings are single-storey dwellings built before 2010 that currently have an inefficient heating or hot water system. The focus on single-storey dwellings is due to the higher installation costs for multistorey buildings. Public housing tenants are not required to participate unless they have a Vulcan or Pyrox heritage gas heater. These older systems can produce excessive carbon monoxide if not installed and maintained properly.

3. Existing knowledge

There is a growing literature examining the determinants (Best and Burke 2019; Chan 2016; Churchill and Smyth 2020; Nelson et al. 2019) and some of the consequences (Churchill and Smyth 2021a) of energy-related financial hardship in Australia. Broadly, those in the family formation stage (with energy customers aged between 21 and 60), with low income, a large household size, and with higher-than-average energy consumption most frequently experience the phenomenon (Nelson et al. 2019). Low-income households are particularly vulnerable to high energy costs if they are also asset poor and consume large quantities of energy. Consequently, some authors have concluded that focusing energy hardship policies on low-income, low-asset families rather than pensioners would lead to more equitable and efficient outcomes (Simshauser 2021). Policy interventions can also target other root causes of energy poverty (Churchill and Smyth 2021b), such as having a family member/s who relies on energy-using medical equipment (Best and Burke 2019).[4]

When it comes to energy consumption, earlier work finds that there is a weak and complex relationship with household income levels in Australia, with some low-income households consuming high levels of energy and some consuming low levels (Bennett, Cooke, and Waddams Price 2002). The use of large amounts of electricity (Australian Energy Regulator 2021; Dodd and Nelson 2022) and natural gas (Nelson et al. 2019) by some hardship

[3] ActewAGL do not publicly report the exact proportion. It is understood, however, that the proportion of public housing dwellings in the priority group is greater than 70 percent.
[4] This has been seen in Australia, with eligible households being able to receive an Essential Medical Equipment Payment (EMEP) to help cover energy costs for medical needs.

customers is linked to factors such as having less efficient appliances (Simshauser and Downer 2016), often natural gas ones in jurisdictions such as the ACT. Despite being vulnerable to energy poverty, pensioners and concession card holders are known to often have lower levels of per-household energy consumption (Simshauser and Downer 2016). However, these households also tend to have fewer household members than the average (Australian Bureau of Statistics 2018).

The rebound effect – the combination of substitution and income effects that follow an energy efficiency improvement due to a decrease in the price of the energy service (Sorrell and Dimitropoulos 2008) – plays an important role in understanding potential responses to energy efficiency improvements. The direct rebound effect involves households increasing their consumption of an energy service when its marginal cost is reduced due to an energy efficiency improvement. For example, the cost of heating a room to a specific temperature reduces after the installation of a more energy-efficient heating system, encouraging more use of heating. Reduced energy costs also increase purchasing power, resulting in an income effect that may result in households increasing their consumption of other energy services. For example, the installation of a more energy-efficient hot water system may free up resources to allow an increase in the use of space heating and lighting. This is the indirect rebound effect. Where they exist, rebound effects reduce the energy consumption savings from energy efficiency improvements.

Prior empirical literature finds that socioeconomically-disadvantaged households in Europe and the Americas may experience smaller average reductions in energy consumption both in total (Davis, Fuchs, and Gertler 2014) and proportionally (Liang et al. 2018; McCoy and Kotsch 2021) than other households after installing energy-efficient appliances. For the former, this is in part because they are likely to consume less energy in the first place. They may also be more responsive to a fall in the price of an energy service, and so experience a larger rebound effect (Chitnis et al. 2014). For instance, during hot weather these households may reduce the temperature in their homes by more than relatively advantaged households after installing an energy-efficient RCAC, a tendency that relates to aspiring to catch up to the living standards of the middle class (Cayla, Maizi, and Marchand 2011). In contrast, households who already consumed at or near their desired level of energy services before an energy efficiency improvement have been found to be less likely to substantially change their consumption of energy services and to instead benefit primarily from reduced energy bills (Milne and Boardman 2000).

In proportional terms, disadvantaged households may be expected to experience relatively large greenhouse gas emission rebounds after an energy efficiency improvement. Studies on this issue typically use derived expenditure or income elasticities and apply various modelling assumptions, with relevant research having been conducted for Australia (Murray 2013), the United States (Thomas and Azvedo 2013), and the United Kingdom (Chitnis et al. 2014). However the absolute size of the rebound effect may well be smaller for lower-income households in situations in which they had lower baseline emissions levels to begin with (Thomas and Azvedo 2013).

Our analysis examines overall final impacts on residential energy use of switching to a new energy-efficient electric appliance rather than separating out the direct and rebound effects. Nevertheless, it is possible that a finding of small (or non-existent) energy use reductions after a switch to a new energy-efficient appliance may be due to rebound effects experienced within the home, for example additional electricity use for cooling purposes subsequent to the installation of an RCAC. The rebound effect is thus an important concept when it comes to interpreting the results. The overall energy use responses of vulnerable households in Australia to energy efficiency improvements have yet to be studied using observed household bill data.

4. Data

4.1. Datasets

We obtained billing data from ActewAGL for all households who received discounts for energy-efficient RCACs and hot water systems through the EEIS over November 2017–December 2020 (3,141) plus a sample of other randomly selected households who did not receive discounts (11,233 households) so as to form a control group.[5] The dataset contains quarterly information on household purchases of grid electricity and of natural gas, plus data on household exports of solar power to the grid in kilowatt hours. It also includes both the installation dates for new electrical appliances under the EEIS and energy meter read dates. The dataset does not include information on the quantity of self-consumption of electricity produced by a household's solar system, as this is not measured by the utility.

The data cover the period 1 January 2015–10 December 2020 and form an unbalanced panel, with households entering the sample late in some cases and exiting the sample if they move residences or change energy retailers. Most households in the ACT do not frequently switch

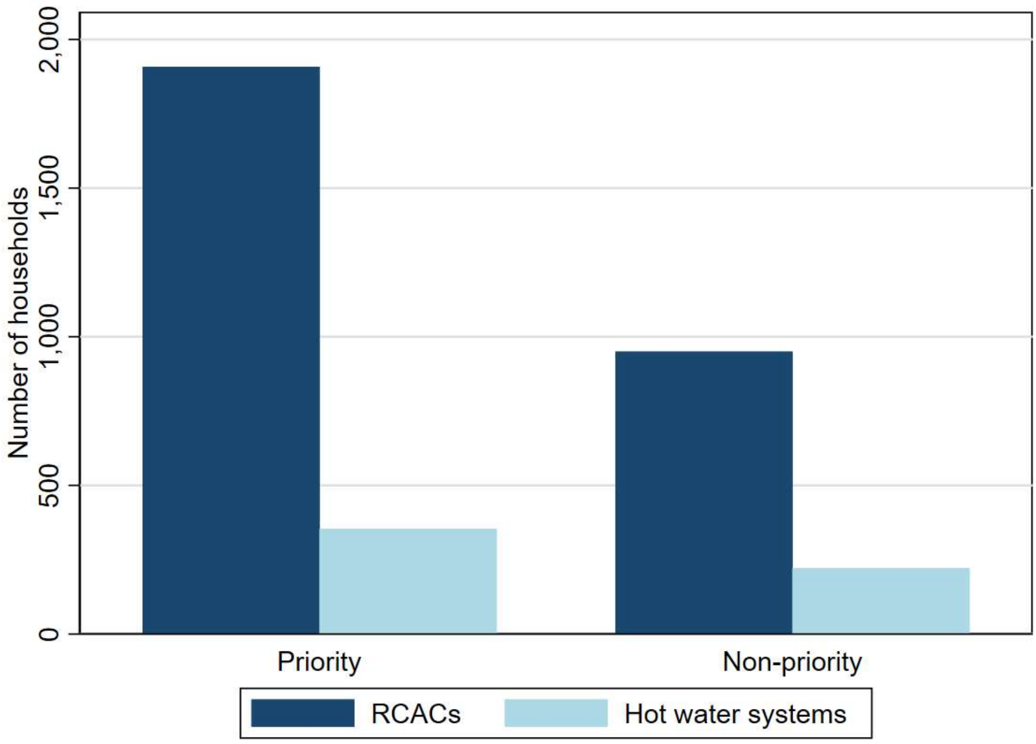
[5] See Appendix A for distributions of the installation dates. We define a household at the billing level.

retailers and continue to be served by ActewAGL (Australian Energy Market Commission 2020).

The analysis also uses information on the numbers of heating and cooling degree days (HDDs and CDDs) based on temperature data from the Australian Government's Bureau of Meteorology. These compare average daily temperatures with a comfort-level temperature. We use a base of 18 degrees Celsius to calculate HDDs and 24 degrees Celsius to calculate CDDs. For example, for a day for which the average temperature is 4 degrees Celsius, the number of HDDs is 14. We match each household's postcode with the nearest of four weather stations using Geographical Information Systems. If data are missing for a weather station on any day, we use the corresponding temperature from the closest alternative weather station.

We focus on households who participated in the EEIS by replacing at least one natural gas appliance. Figure 1 compares the numbers of priority and non-priority households who replaced their natural gas appliances over November 2017–December 2020 under the EEIS, by new appliance type. Households are measured as priority or non-priority based on their characteristics when they signed up to participate in the scheme. It can be seen that most of the discounts were for new RCACs to replace existing natural gas heaters. The exact types of heaters and hot water systems that were replaced by each household are not available in the dataset, other than whether they were electric or natural gas systems.

Figure 1: Number of households with discounts to replace a natural gas appliance under the EEIS, by priority status



Notes: Data provided by ActewAGL. The figure shows all households in the full dataset who replaced a natural gas appliance under the EEIS over November 2017–December 2020, including those who also replaced an electric appliance. Households are counted twice in the figure if they replaced both a gas heater and a gas hot water system.

4.2. Exclusion criteria

Based on discussions with ActewAGL, and to reduce exposure to outliers and potential data errors, we analyze a final sample that excludes households:

- With negative recorded values for either electricity (grid only) or natural gas consumption in any billing quarter. Negative values arise due to inaccurate entries, for example due to mismeasurement.
- With zero electricity consumption from the grid in a billing period, which may indicate either mismeasurement or a dwelling being vacant. If a household has zero grid electricity consumption in the first and/or last quarter for which they are in the sample (likely because they have moved residences without immediately opening and/or closing their accounts) and positive grid electricity consumption in all other quarters, we drop only their first and/or last billing quarter.
- With grid electricity consumption above 20,000 kWh or natural gas consumption above 120,000 MJ in any quarter so as to remove some potentially inaccurate large entries.

These threshold values were chosen based on visual inspection of the right-hand tails of histograms of the variables.

- With zero natural gas consumption in the quarter prior to the first installation of a new RCAC or hot water system under the EEIS.
- With a missing energy bill for the quarter before and/or after the quarter of the first treatment.
- Who replaced an electric resistance room heater and/or hot water system but not a natural gas system under the EEIS.

The final sample consists of 1,606 treatment households and 5,492 control households, making a total of 7,098 households. Among the treatment households, 986 are priority and 620 are non-priority households under the EEIS classification. 947 of these priority households replaced natural gas heaters with electric RCACs and 193 replaced their natural gas hot water systems with electric alternatives under the EEIS, with some households doing both. For the non-priority households, the corresponding numbers were 555 for RCACs and 77 for hot water systems. Data are available for an average of 14.86 quarters for each household in the sample. Data on whether each priority household lives in public housing or whether householders are pensioners are not available.

4.3. Descriptive statistics

Table 2 provides descriptive statistics. Data are shown for each of the three household groups: (1) priority households who received the treatment; (2) non-priority households who received the treatment; and (3) control households who did not receive the treatment. A column is also shown for the full sample. The control group cannot be split into priority and non-priority households given that households are only registered as priority households when they participate in the EEIS. Control households are expected to be generally representative of the population of ACT households given that the group was randomly selected by ActewAGL.

Based on *t*-tests for the averages in Table 2, priority treatment households on average consumed more purchased energy in energy content terms than control households (18,407 MJ per quarter compared to 15,709 MJ) over 2015–2017. The higher energy use of priority households reflects the fact that these households were relatively gas dependent prior to participating in the EEIS, hence their participation in the scheme. Table 2 also shows that the priority treatment households had similar use of grid electricity to the control households. Self-generated solar electricity use is likely to have been smaller for the priority treatment households given the small average size of their solar exports as shown in Table 2.

Table 2: Descriptive statistics for the estimation sample

	Treatment		**Control**	**All**
	Priority households	**Non-priority households**		
Billing quarter averages in pre-treatment period:[a]				
Natural gas consumption (MJ)	11,639.25	15,113.81	8,914.39	10,340.23
	(12,621.70)	(17,157.76)	(14,571.05)	(14,689.99)
Grid electricity consumption (kWh)	1,879.90	1,804.98	1,887.50	1,874.98
	(1,767.36)	(1,730.11)	(1,605.22)	(1,659.84)
Total energy consumption (MJ)	18,406.90	21,611.72	15,709.40	17,090.15
	(15,735.45)	(19,684.04)	(16,025.84)	(16,617.70)
Solar exports (kWh)	39.06	221.96	137.60	126.46
	(279.88)	(634.64)	(448.70)	(450.56)
Percentage of households with:				
RCAC replacements[b,c]	95.64	89.52	0	21.10
Hot water replacements[b,c]	19.37	12.26	0	3.76
Electric-to-electric treatment[b]	0.61	0.16	0	0.10
Solar exports to grid[a]	2.84	17.74	6.55	7.02
No. bills per household (full sample)	20.46	19.59	13.32	14.86
	(5.28)	(6.07)	(8.38)	(8.34)
No. observations (full sample)	20,174	12,147	73,170	105,491

Notes: Standard deviations are in parentheses. Exclusion criteria applied (see section 4.2). Total energy consumption excludes self-generation. The average per-quarter solar exports for households with solar PV panels during 2015–2017 were 1,226.43 kWh (priority households), 975.88 kWh (non-priority households), 946.04 kWh (control households), and 968.52 kWh (all households).

[a] These variables are based on bills during 2015–2017.

[b] Each household is counted only once in these calculations.

[c] These are natural gas-to-electric treatments.

Table 2 also indicates that, like the priority treatment households, non-priority treatment households had higher average levels of natural gas consumption than the control households during 2015–2017, reflecting a greater underlying incentive to participate in the EEIS. Based on *t*-tests of means, they also had slightly lower average levels of grid electricity consumption and higher rates of solar PV ownership than the other households in the sample.

The energy use data in Table 2 for the control households are similar to data from other sources. For instance, a report by Frontier Economics suggests that households in the ACT on average consumed around 6,407 kWh of grid electricity and 34,927 MJ of natural gas annually in 2019 (Frontier Economics 2020). The control households in this study on average consumed about 7,550 kWh $(1{,}887.50 \times 4)$ of grid electricity and 35,6586 MJ $(8{,}914.39 \times 4)$ of natural gas annually over the period 2015–2017.

5. Methods

5.1. Econometric model specification

Households who received ActewAGL energy efficiency discounts to install new electric appliances may differ from others along various dimensions, including their socioeconomic characteristics and preferences for environmental conservation. Omitted variable bias may arise if these variables are unobserved and influence both a household's propensity to switch to a more energy-efficient appliance and their energy consumption. There is also a potential for simultaneity bias: households who consume more energy face greater incentives to install energy-efficient technologies (in this case electric alternatives to existing natural gas appliances). As such, a simple regression of energy consumption on whether a household switched to a more energy-efficient appliance may yield biased results.

Fixed effects models can help to address omitted variable bias by controlling for household and other characteristics that are fixed over time and also for time-specific factors that influence households similarly. Our main specification is:

$$E_{h,q} = \beta_1 RCAC_{h,q} \times priority_h + \beta_2 hotwater_{h,q} \times priority_h + \beta_3 RCAC_{h,q} \times nonpriority_h + \beta_4 hotwater_{h,q} \times nonpriority_h + \boldsymbol{X'_{h,q}}\alpha + \gamma_{h,qoy} + \delta_{g,q} + \varepsilon_{h,q} \qquad (1)$$

where the dependent variables are: (1) grid electricity consumption (MJ); (2) natural gas consumption (MJ); (3) total energy consumption (excluding self-generation of solar; MJ); and (4) estimated greenhouse gas emissions responsibility (kg of CO_2-e) of household h in quarter q. To directly estimate both level and proportional effects we use both (1) the unlogged energy consumption variables and (2) the log of the energy consumption variables. The error term $\varepsilon_{h,q}$ captures unobserved factors affecting energy consumption. We cluster standard errors at the household level to allow for potential serial correlation within households.

The two treatment variables, $RCAC_{h,q}$ and $hotwater_{h,q}$, equal one if household h had a new electric RCAC and/or hot water system installed via the EEIS to replace a natural gas appliance in quarter q, and zero otherwise. For installations that occur during a billing period, the value of the treatment variable equals the proportion of the quarter that is treated. The treatment variables remain at 1 in all quarters after the quarter of initial treatment.

The variables $priority_h$ and $nonpriority_h$ equal one if a household is a priority or non-priority household, respectively, and zero otherwise. The coefficients β_1 and β_3 therefore measure the average treatment effect of installing a new RCAC for priority and non-priority households, respectively. The coefficients β_2 and β_4 have the same interpretation for the hot water system replacements. We use F-tests to investigate whether impacts depend on the level of household vulnerability as measured by priority status.

Vector $X'_{h,q}$ controls for other key variables that may change over time and affect both energy consumption and the propensity to switch appliances. For households who also replaced an electric resistance (rather than natural gas) heater or hot water system with a new electric alternative under the EEIS, we include a control equal to the proportion of time in a billing quarter for which the household had the new electric appliance. We also control for the household's quarterly exports of solar electricity to the grid (kWh), as these may be correlated with the treatment variables through a wealth channel (Best, Burke, and Nishitateno 2019) or via household preferences for energy autonomy and/or environmental conservation (Alipour et al. 2020). Having access to solar PV is also likely to reduce the extent to which new electric appliances lead to increases in use of grid electricity, as solar households would tend to reduce their solar exports when their solar self-consumption increases.[6]

The $X'_{h,q}$ vector also controls for if a household is on a time-differentiated electricity tariff in a billing quarter. Altogether, there are four types of tariffs in the ACT: flat-rate, time-of-use, demand, and controlled load.[7] Some households switch between tariffs over time. The dataset does not allow us to directly identify the type of tariff a customer is on in each quarter, so we use information about the household's consumption in each billing quarter to form a proxy for whether a household is on a time-differentiated tariff. Specifically, we construct a variable equal to one if the customer had positive recorded grid electricity consumption for the shoulder, off-peak, and/or controlled load time period in a quarter, and zero otherwise. For

[6] The earliest solar feed-in tariff for the ACT used gross metering, paying households for every unit of electricity generated. However, it is understood that most solar households in the sample are on the more recent net metering arrangements, under which solar output is self-consumed and only excess solar is exported.

[7] With a time-of-use tariff, households pay different charges based on the time of day they consume energy. With a demand tariff, ActewAGL customers face a surcharge based on their maximum electricity consumption from the grid for any thirty-minute interval between 5–8pm during a given month. The other tariffs can be combined with a controlled load tariff, which enables customers to charge energy hungry appliances (such as an electric hot water system) at lower cost if they agree to charge them within limited time-periods during the day.

households who are not on a time-differentiated tariff, data for use of electricity from the grid are only available for total consumption over the full quarter.

We also control for factors such as weather and seasonality. First, we include quarter-by-group fixed effects, $\delta_{g,q}$, to control for any unobserved factors that have approximately equal impacts on the households in each group in each quarter. There are 23 of these fixed effects for each group, ranging from quarter 2 of 2015 to quarter 4 of 2020. These also control for any differences in the trajectories of the energy consumption variables related to household vulnerability.

We also include fixed effects, $\gamma_{h,qoy}$, for each household by quarter-of-year (four dummy variables per household), as energy consumption may also follow seasonal trends that are individual to each household based on factors such as the level of thermal insulation in their dwelling. This approach is more rigorous than including household fixed effects (one dummy variable per household), while still ensuring that household time-invariant factors are fully controlled for.[8] The household by quarter-of-year fixed effects also partially control for differences in the timing of when ActewAGL reads the energy meters of individual households. We also include the numbers of CDDs and HDDs, respectively, in the 90 days prior to an electricity meter reading. These variables are not perfectly correlated with the quarter-by-group fixed effects as they differ for individual households at any one time.

5.2. Estimated greenhouse gas emissions responsibility

Alongside impacts on energy consumption, we also analyze the effects of the new electric installations on greenhouse gas emissions. To do so we allocate emissions to households by multiplying their consumption of grid electricity and natural gas with relevant emissions factors.[9] For natural gas, greenhouse gas emissions are calculated using the emissions factor for gas from a distributed pipeline from Australia's 2020 National Greenhouse Accounts Factors (Department of Industry, Science, Energy and Resources 2020). This is 0.052 kg CO_2-e/MJ.

We use two approaches for the greenhouse gas emissions factor for residential use of electricity from the grid. The first is to use the scope 2 emissions factor for the New South Wales (NSW)-ACT electricity grid region, which was 0.81 kg CO_2-e/kWh in 2020

[8] Household by quarter-of-year fixed effects are perfectly collinear with household fixed effects but more flexible in that households are allowed to display different seasonal patterns. Including household fixed effects in addition would make no difference to the estimation results.
[9] For recent calculations of emissions savings at the appliance level, see Pistochini et al. (2022).

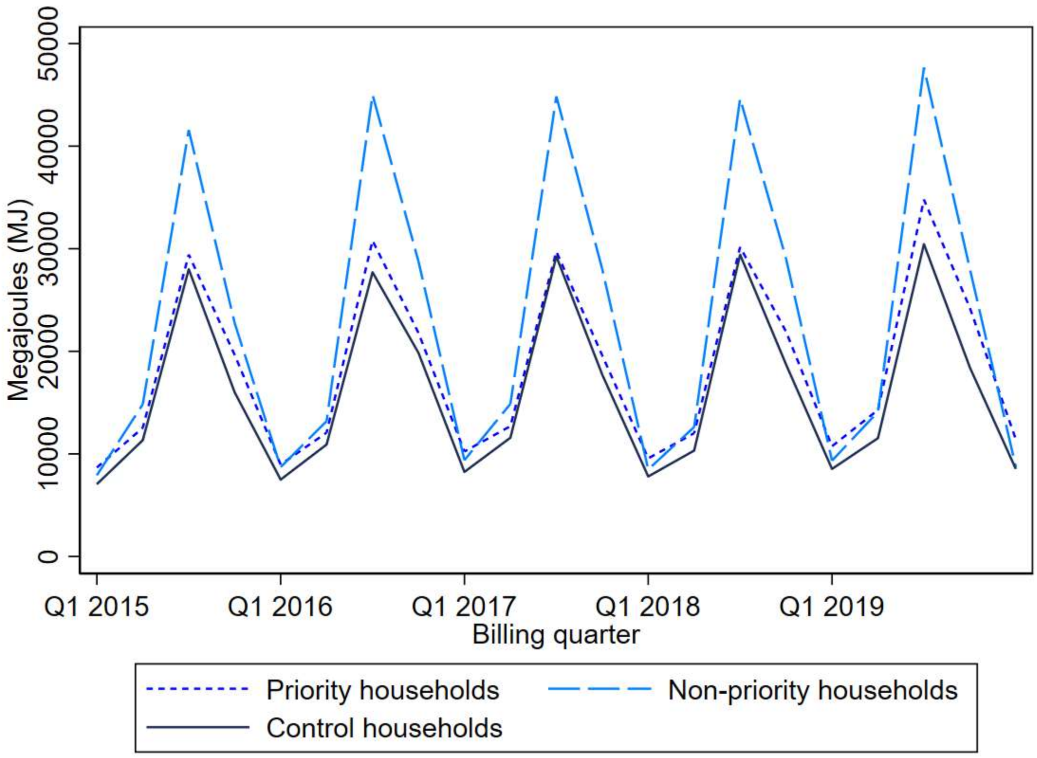
(Department of Industry, Science, Energy and Resources 2020). This covers the electricity required to supply final residential consumers, including transmission and distribution losses.[10] One interesting characteristic of the ACT, however, is that the ACT Government has set a target of 100 percent renewable electricity. This target has been notionally achieved since 2019 via the use of renewable electricity contracts for supply into the broader national electricity market (NEM). Specifically, the ACT Government matches every kilowatt hour of electricity consumed from the grid in the ACT with a kilowatt hour produced by one of its contracted renewable energy projects in the NEM (although note that production and consumption times do not exactly match). In our second approach we thus apply an emissions factor for electricity of zero in recognition of the fact that ACT use of electricity from the grid is offset by renewable electricity purchases under this mechanism.

5.3. Seasonality

Figure 2 plots the average levels of total energy consumption (natural gas plus electricity, in MJ) for each quarter from Q1 2015 to Q1 2020 by household group, excluding households who received an appliance upgrade under the EEIS over this period. The high degree of seasonality of ACT residential energy use is visible. The patterns for the priority and control households are similar, while non-priority households have a more pronounced winter peak. This is consistent with this group tending to be larger natural gas users (see Table 2). These differences provide support for controlling for quarter-by-group fixed effects.

[10] In contrast, the energy use measures that we use are for residential energy usage only and do not include the additional requirements in the upstream energy supply system to supply this energy.

Figure 2: Average quarterly energy consumption by household group and billing quarter, Q1 2015–Q1 2020



Notes: Households in this figure are those for whom energy bills are available for each quarter over Q1 2015–Q1 2020. Data are quarterly. Exclusion criteria are applied (see section 4.2). Households who received an appliance upgrade in or before Q1 2020 are excluded from the figure. Energy is grid electricity plus natural gas. The priority and non-priority households are treatment group households.

5.4. Identification issues

The identification assumption for our fixed effects model is that, conditional on the controls, households switch to a more energy-efficient electric air-conditioning or hot water system in a way and with timing that is as good as random. This may hold quite well for the public housing tenants, as these households did not purchase the appliances themselves; instead, the public housing authority, Housing ACT, decided which types of dwellings would be eligible for the upgrades and played the key role in deciding when the upgrades would occur. However it is also the case that the tenants may also have taken active steps to register for an upgrade.

For non-public housing households, there is greater risk that unobservable household or dwelling characteristics may have influenced both the decision to replace an appliance and that household's energy consumption. The program was voluntary, meaning that the characteristics of the households who chose to participate in the program likely differ from those who did not. Households may also have decided to switch to a more energy-efficient electric appliance in part due to changes in employment status or household size over time

(Davis, Fuchs, and Gertler 2014; Fowlie, Greenstone, and Wolfram 2018), which we do not have data on. However it is likely that many of the households who purchased the discounted energy-efficient appliances did so when their old, less energy-efficient appliances reached the ends of their useful lives (Alberini, Gans, and Towe 2016). If so, the timings of the treatments may be relatively random.

Another potential source of omitted variable bias arises because the dataset does not contain information on whether households installed RCACs or hot water systems without receiving discounts under the EEIS. Some households may have chosen to not participate in the EEIS but install a new electric appliance anyway. However the scheme was open to all and the discounts offered by ActewAGL were large enough that many households would have chosen to pursue these offers if installing an eligible appliance. Some households may have installed several new heating or cooling appliances concurrently. If so, our estimations of the effects of EEIS installations may be inflated. However, in 2012 only about one-fifth of households in the ACT who had an RCAC had more than one (Australian Bureau of Statistics 2013), so this is unlikely to have been a major issue.

Some of the households also participated in other relevant schemes for which we do not have complete data. Through free visitations, the ACT's Home Energy Efficiency Program offers in-home energy assessments, tips on how to save energy, energy saving kits, draught proofing, and referrals to other services for low-income households. There has also been an ActewAGL fridge buyback scheme under which ActewAGL collects old fridges and freezers to ensure they are recycled responsibly, applying an A$30 credit to the customer's electricity bill. ActewAGL customers who live in the ACT and have a working fridge or freezer have been able to participate in this scheme.

Our dataset does not include detailed information about household participation in the Home Energy Efficiency Program. However, the ACT Government provided us with some aggregate statistics on when priority treatment households who live in public housing were visited as part of the Home Energy Efficiency Program versus when new appliances were installed in their homes through the EEIS. We also have access to data for some households who participated in the fridge buyback scheme. Appendix B reveals that there are typically considerable time gaps between when households installed the energy efficiency upgrades and their participation in the other schemes. In section 6.4 we will examine the robustness of our estimations to household involvement in the fridge buyback scheme.

The analysis identifies the impacts of switching to more energy-efficient electric appliances under the EEIS rather than impacts of the ActewAGL energy efficiency discounts themselves. Many households who participate in energy efficiency programs are likely to be inframarginal, meaning they would have upgraded to a more energy-efficient appliance even without financial incentives (Joskow and Marron 1992). Estimates of the free-ridership rate for opt-in schemes are often around 50 percent or more (Rivers and Shiell 2016). Measuring the causal impact of the ActewAGL discounts program would require analyzing changes in the types of appliances purchased by households in the ACT relative to a counterfactual scenario without the discounts. While such analyses have been pursued in other contexts (Boomhower and Davis 2020; Houde and Aldy 2017), this is beyond the scope of this paper.

6. Results

6.1. Energy consumption (unlogged)

Table 3 reports effects on energy consumption in MJ per quarter (unlogged). As expected, impacts on natural gas consumption are negative in point estimate terms, while impacts are positive for consumption of grid electricity for both types of appliance replacements and each of the household types. On average the RCACs led to a reduction in household natural gas use of about 7,000 MJ per quarter and an increase in household grid electricity use of about 1,350 MJ per quarter. For comparison, a typical natural gas heater can consume up to about 28 MJ per hour of use (O'Neill 2020). The estimated impacts on total energy consumption are larger for the RCACs than for new hot water systems. Using marginal prices prevailing in 2020, the RCACs have been associated with about an A$144 per quarter reduction in energy bills.[11] This is despite them being able to be used for the additional function of cooling in summer.

There are some key differences between the treatment effects for the priority and non-priority households who installed hot water heat pumps in Table 3. Priority households on average reduced their natural gas consumption and increased their electricity consumption from the grid by more than non-priority households. Overall, priority households also experienced a larger average decrease in total energy consumption than non-priority households due to their new hot water systems under the EEIS. While the hot water system coefficients for natural gas consumption and total energy consumption for the non-priority group are not statistically

[11] We use a marginal electricity price of A$24.742c/kWh, the GST-inclusive price under ActewAGL's Home Plan in 2020, and a marginal natural gas price of A$3.3761c/MJ, the GST-inclusive price for ActewAGL's second usage block for residential natural gas consumption in 2020.

significant, there were relatively few non-priority households who installed hot water systems under the EEIS in the sample; only around 1 in 7 non-priority households in the treatment group. This likely contributes to the relatively large standard errors for these estimates.

Table 3: Energy consumption impacts, dependent variables in MJ per quarter

	(1) Natural gas	(2) Grid electricity	(3) Total
Priority households			
$RCAC_{h,q}$	-7,491.91***	1,339.51***	-6,152.40***
	(408.05)	(161.22)	(391.11)
Hot $water_{h,q}$	-7,049.21***	3,208.53***	-3,840.69***
	(934.58)	(522.31)	(816.30)
Non-priority households			
$RCAC_{h,q}$	-6,608.79***	1,373.56***	-5,235.23***
	(698.34)	(232.33)	(685.69)
Hot $water_{h,q}$	-1,795.64	1,114.38*	-681.26
	(1,578.12)	(627.00)	(1,542.46)
F-tests for priority status			
Stat. sig. diff.: RCACs	NO	NO	NO
	(p = 0.27)	(p = 0.90)	(p = 0.24)
Stat. sig. diff.: hot water systems	YES	YES	YES
	(p = 0.00)	(p = 0.01)	(p = 0.07)
Observations	105,491	105,491	105,491
Households	7,098	7,098	7,098
R-squared	0.83	0.87	0.85
Adj. R-squared	0.77	0.83	0.81

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include X-vector covariates, quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Coefficients on other explanatory variables are reported in Appendix C. Exclusion criteria applied (see section 4.2). Total energy consumption excludes self-generation.

Based on a simple engineering-based calculation involving multiplying the power consumption of a new hot water heat pump by the number of hours during the day that this system is expected to be running on average and the number of days in a quarter, the average household who installs a new hot water system could be expected to increase their grid electricity consumption by around 1,100 MJ per quarter. This is similar to the estimated coefficient in Table 3 for the non-priority households but considerably smaller than that for the priority households.

Many of the priority households who installed hot water systems also installed RCACs within a similar timeframe, raising concerns about possible conflation of effects. Specifically, of the priority households who installed hot water systems, 66 percent (128 households) also installed an RCAC within the same year. The figure is 16 percent (12 households) for the non-priority households. Table 4 presents additional estimations for impacts on natural gas and grid electricity consumption. Columns (1) and (3) include interactions between the RCAC and hot water variables, with the interactions equal to the proportion of the billing quarter during which a household had both types of new appliances, respectively. Columns (2) and (4) exclude households who installed both types of energy-efficient appliances during the sample period, with no interactions.

The estimated coefficients for the hot water systems in Table 4 are smaller than in Table 3 for both natural gas and grid electricity consumption. Much more consistent effects are found for RCACs, which were more commonly installed. We thus conclude that some of the impacts of the installations of new hot water systems on grid electricity and natural gas consumption are difficult to disentangle from the effects of RCAC installations given that (a) some households adopted both appliance types at a similar point in time and (b) only a small share of households installed new hot water systems under the EEIS. Nonetheless, the estimated impacts on gas consumption from the new hot water installations remain smaller for the non-priority households than the priority households.

Based on Table 2, non-priority households in the treatment group are more likely to have access to rooftop solar PV than priority households. To test whether the non-priority households went on to reduce their exports of solar electricity to the grid after the installation of new hot water systems, we explored regressing the quarterly solar exports variable on the treatment variables and the other *X*-vector covariates (results not reported). No evidence was found that the solar exports of non-priority households reduced relative to those of priority households as a result of the new hot water systems.

Table 4: Additional grid electricity and natural gas consumption impacts, dependent variables in MJ per quarter

	Natural gas		Grid electricity	
	(1)	(2)	(3)	(4)
Priority households				
$RCAC_{h,q}$	-7,229.89***	-6,982.68***	1,125.75***	1,082.70***
	(409.07)	(403.33)	(159.45)	(146.67)
Hot $water_{h,q}$	-4,309.36***	-3,226.52***	968.08*	681.35
	(1,241.12)	(1,234.40)	(531.67)	(486.35)
$RCAC_{h,q}$*Hot $water_{h,q}$	-4,394.75**		3,538.36***	
	(1,724.35)		(898.07)	
Non-priority households				
$RCAC_{h,q}$	-6,029.97***	-6,025.19***	1,235.26***	1,260.56***
	(606.92)	(606.58)	(195.67)	(195.63)
Hot $water_{h,q}$	125.66	384.15	652.68	484.52
	(1,360.75)	(1,432.16)	(462.27)	(459.61)
$RCAC_{h,q}$*Hot $water_{h,q}$	-11,615.96*		2,818.40	
	(5,502.43)		(2,843.59)	
F-tests for priority status				
Stat. sig. diff.: RCAC only	NO	NO	NO	NO
	(0.10)	(0.19)	(p = 0.67)	(p = 0.47)
Stat. sig. diff.: hot water system only	YES	YES	NO	NO
	(0.02)	(0.06)	(p = 0.65)	(p = 0.77)
Observations	105,491	102,217	105,491	102,217
Households	7,098	6,932	7,098	6,932
R-squared	0.83	0.83	0.87	0.87
Adj. R-squared	0.77	0.78	0.83	0.82

Notes: *** p<0.01, ** p<0.05, * p<0.1. Both regressions include X-vector covariates, quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Coefficients on other explanatory variables not reported. Exclusion criteria applied (see section 4.2). Columns (2) and (4) also exclude households who installed both types of energy-efficient appliances from the sample. Columns (1)–(2) are for natural gas and columns (3)–(4) for grid electricity. Total energy consumption excludes self-generation.

6.2. Log energy consumption

Table 5 presents estimates for logged energy consumption variables. Column (1) excludes households who had zero natural gas consumption in a quarter. The treatment effects can be interpreted as the change in the log of the relevant energy consumption variable from switching to a new energy-efficient electric appliance, holding all else constant. This translates into a percentage change in the energy consumption variable of $100 \times [exp(\hat{\beta}) - 1]$, where β is the estimated treatment effect (Wooldridge 2019).

Table 5: Energy consumption impacts, log-transformed MJ per quarter dependent variables

	(1) Log natural gas	(2) Log grid electricity	(3) Log total
Priority households			
$\text{RCAC}_{h,q}$	-0.59***	0.18***	-0.28***
	(0.04)	(0.02)	(0.02)
$\text{Hot water}_{h,q}$	-0.69***	0.10***	-0.12***
	(0.13)	(0.04)	(0.04)
Non-priority households			
$\text{RCAC}_{h,q}$	-0.55***	0.23***	-0.21***
	(0.07)	(0.03)	(0.03)
$\text{Hot water}_{h,q}$	-0.57***	0.12	-0.13**
	(0.17)	(0.07)	(0.06)
F-tests for priority status			
Stat. sig. diff.: RCACs	NO	NO	YES
	(p = 0.59)	(p = 0.18)	(p = 0.06)
Stat. sig. diff.: hot water systems	NO	NO	NO
	(p = 0.57)	(p = 0.84)	(p = 0.89)
Observations	80,370	105,491	105,491
Households	5,340	7,098	7,098
R-squared	0.86	0.85	0.88
Adj. R-squared	0.81	0.80	0.84

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include X-vector covariates, quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Coefficients on other explanatory variables are reported in Appendix C. Exclusion criteria applied (see section 4.2). Total energy consumption excludes self-generation.

The estimates for natural gas in Table 5 are quite large, ranging from an approximate 42 percent decrease for non-priority households who installed RCACs to a roughly 50 percent decrease for priority households who replaced their hot water systems. In 2015, about 18 percent of the natural gas consumed in the residential sector in the ACT was for water heating and 80 percent for space heating, with the remaining 2 percent for cooking (Energy Rating 2017). The key reason why the percentage reduction in natural gas use for households who replaced their hot water systems is larger than 18 percent may be that these households did not all have natural gas heaters. Hot water heating may thus have dominated their initial use of natural gas.

The estimates in Table 5 indicate that switching to a new electric RCAC has on average led to an increase in grid electricity consumption of approximately 20 percent for the priority households and 26 percent for the non-priority households. The increase in grid electricity use arising from the electric hot water system installs is estimated to be about 11 percent for the priority households and 13 percent for the non-priority households. The proportional increases in grid electricity consumption are smaller than the proportional decreases in natural gas use. This makes sense given the more varied uses of electricity in the residential sector; water and space heating are among many uses of electricity, whereas they contribute large shares of residential natural gas use if natural gas appliances are used.

Overall, the *F*-tests in Table 5 indicate that priority and non-priority households experienced quite similar percentage decreases in natural gas consumption and quite similar percentage increases in grid electricity consumption following the energy efficiency upgrades. Priority households who installed RCACs experienced larger percentage decreases in total energy consumption (excluding self-generation) than non-priority households. This is due to both their lower initial levels of energy use (see Table 2) and their sizeable reduction in total energy use after switching from a natural gas heater to an RCAC (Table 3). There is no statistically significant difference between the priority and non-priority households in the percentage decline in overall energy use (excluding self-generation) after the installation of a new hot water system.

6.3. Greenhouse gas emissions

We next turn to estimates for effects on greenhouse gas emissions. Columns (2)–(3) of Table 6 use the emissions factor for grid electricity in the NSW-ACT region. Using this approach, there are negative overall impacts on total emissions from the new RCACs, although the effect is not significantly different from zero for the non-priority group. For hot water system replacements, there is evidence of an increase in greenhouse gas emissions on average, with the reductions in emissions from natural gas consumption not offsetting the increases in emissions linked to grid electricity consumption. The estimates imply that a hot water system switch would lead to greenhouse gas emissions rising by an average of approximately 359 kg CO_2-e per quarter for priority households in the treatment group. While the coefficient of 158 kg CO_2-e per quarter for the non-priority group is also positive, it is imprecisely estimated and not significantly different from zero.

Table 6: Greenhouse gas emission impacts, dependent variables in kg CO_2-e per quarter

	(1) Natural gas	(2) Grid electricity	(3) Total
Priority households			
$RCAC_{h,q}$	-386.06***	301.39***	-84.67**
	(21.03)	(36.27)	(36.05)
Hot $water_{h,q}$	-363.25***	721.92***	358.67***
	(48.16)	(117.52)	(102.79)
Non-priority households			
$RCAC_{h,q}$	-340.55***	309.05***	-31.50
	(35.99)	(52.27)	(56.56)
Hot $water_{h,q}$	-92.53	250.74*	158.21
	(81.32)	(141.08)	(143.76)
F-tests for priority status			
Stat. sig. diff.: RCACs	NO	NO	NO
	(p = 0.27)	(p = 0.90)	(p = 0.43)
Stat. sig. diff.: hot water systems	YES	YES	NO
	(p = 0.00)	(p = 0.01)	(p = 0.25)
Observations	105,491	105,491	105,491
Households	7,098	7,098	7,098
R-squared	0.83	0.87	0.88
Adj. R-squared	0.77	0.83	0.84

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include X-vector covariates, quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Coefficients on other explanatory variables are reported in Appendix C. Exclusion criteria applied (see section 4.2).

The implied increases in greenhouse gas emissions after installations of new electric hot water systems observed in column (3) of Table 6 are linked to the relative lack of energy use savings observed in Tables 3–4 for hot water systems compared to RCACs. They are also due to the relatively high emissions intensity of electricity on the NSW-ACT grid, which remained largely coal dependent in 2020. As the electricity grid increasingly decarbonizes, emissions reductions become more likely. A rise in emissions should be a temporary phenomenon.

Our second approach to calculating the emissions effects of the new electric appliance installations is to use a zero emissions factor for grid electricity, justified by the fact that the ACT has achieved a 100 percent renewable electricity target via the use of renewable electricity contracts. Using this approach, the relevant effect on emissions is given by only the impact on emissions from natural gas in column (1) of Table 6; increases in electricity use have no emissions implications. Reductions in natural gas use are estimated to have resulted in greenhouse gas emission reductions of over 300 kg CO_2-e per quarter on average for households (both priority and non-priority) who installed RCACs. There is also evidence that the hot water system replacements led to reductions in greenhouse gas emissions via reduced natural gas use among priority households. This effect is not statistically significant for the non-priority households.

Table 6 finds no statistically significant differences by priority status for the emissions effects for households who installed new RCACs. Under approach 1 (using the NSW-ACT emissions factor for grid electricity), there is no statistically significant difference in the total effect on emissions between priority and non-priority households who installed hot water systems under the EEIS. Using approach 2 (zero emissions factor for electricity), the reduction in emissions has been larger for priority households who participated in the EEIS than for non-priority households given a larger reduction in natural gas use.

6.4. Robustness

We also explored estimations for: (1) a balanced panel of households who have bills available for every quarter over quarter 1 2015–quarter 3 2020; and (2) an unbalanced panel excluding households who both received a new RCAC or hot water system under the EEIS and participated in the ActewAGL fridge buyback scheme. The results (not reported) were similar to the main estimates, with the estimated coefficients typically remaining within one standard error of the main results.

7. Discussion and conclusion

This paper contributes to the literature on how adoption of new energy-efficient electric appliances influences household energy use and emissions outcomes. Using the EEIS in the ACT as a case study, we examined the impacts of appliance switching on household energy consumption and carbon footprints. We found large decreases in natural gas consumption and smaller increases in grid electricity consumption (in MJ) subsequent to the installation of each type of appliance. In net terms, energy use reductions were generally achieved. The principal energy efficiency and emissions reduction benefits of the EEIS appear to be from the replacement of inefficient natural gas heaters with modern RCACs. The new RCACs also have the advantage of being able to be used for cooling in summer.

The study measures the net final impacts of switching appliances under the EEIS on energy purchased from the grid. These are a combination of the increased energy efficiency of the systems, the potential use of more electricity for cooling in the case of the RCACs, and other potential rebound effects. The data do not enable us to separately identify the sizes of these individual channels. If rebound effects did occur, they would have tended to reduce the overall energy savings from the scheme.

The findings point a spotlight on the importance of decarbonizing electricity grids for the electrification agenda. If electricity generation is zero-carbon, the estimates suggest large emission reductions from the EEIS, especially from switching away from old gas heaters. However, we also found that switching to electric RCACs and hot water systems leads to only small greenhouse gas emission reductions from households or even potentially increased emissions in the short term if a grid-region average emissions intensity for electricity is applied. In the context of the ACT, applying an emissions factor of zero for grid electricity can be justified given the achievement of a 100 percent renewable electricity commitment via the use of contracted renewables projects in the NEM. The renewables commitment has thus been important for the realization of emissions reductions from the EEIS.

Overall, the results imply that the approach of focusing on vulnerable consumers can produce a "double dividend" of both improving social equity while simultaneously achieving environmental benefits. Indeed, the largest emissions reductions from reduced natural gas use have tended to be among priority households. While these households also increased their use of electricity from the grid, if this electricity is from zero- or low-carbon sources then overall emissions reductions are possible.

A potential limitation of our approach is that priority and non-priority households received different discounts to incentivize their appliance switches under the EEIS; public housing tenants received the installations cost-free, whereas other priority households received larger discounts than non-priority households in some instances (see Table 1). We are unable to separate the effects of the appliance switching from effects that arise due to differences in the discounts. Alberini et al. (2016) found that households who received larger financial incentives for switching to more energy-efficient (heating) appliances reduced their energy consumption by less than households who received smaller incentives. Future studies may be able to examine a context in which identical discounts are offered to all households.

There are various other possibilities to extend this research. Future researchers could potentially investigate the role of vulnerability in influencing how households respond to energy efficiency improvements in other contexts, for example the installation of new insulation. Research could also potentially examine whether similar findings are obtained using other measures of vulnerability such as whether individual households experience energy-related financial hardship. Such research is potentially valuable as governments pursue dual objectives of addressing energy poverty and reducing emissions.

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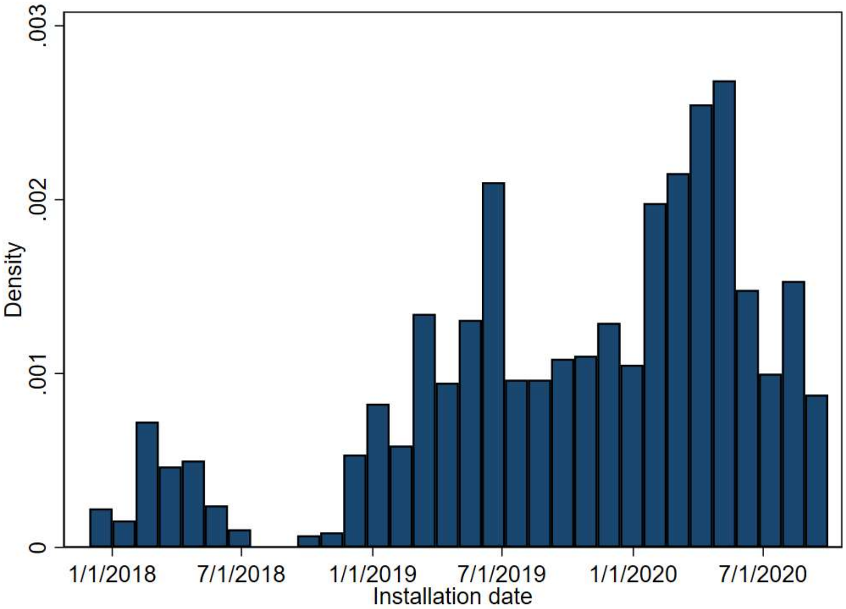
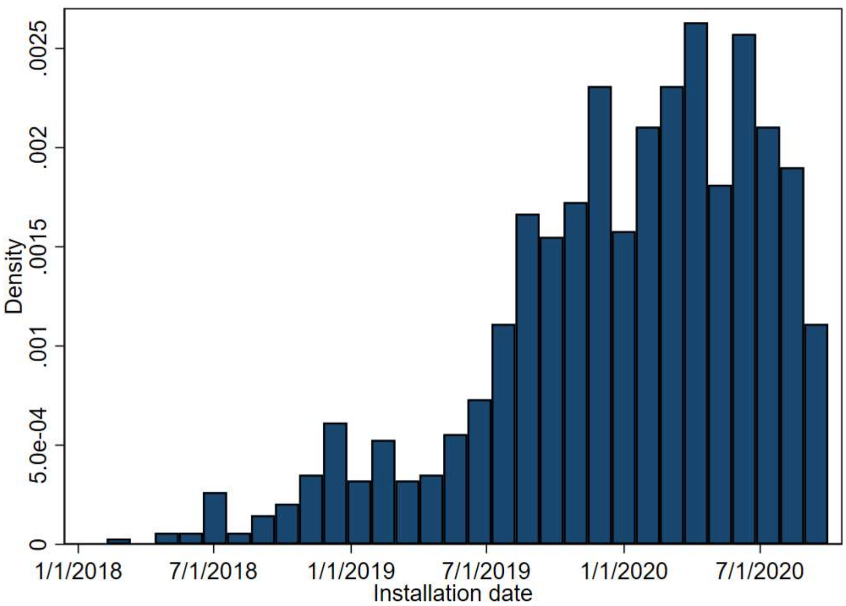
Appendix A: Dates of installations of RCACs and hot water systems under the EEIS

Figure A.1. Installation dates of RCACs and hot water systems for priority households under the EEIS



Notes: Data provided by ActewAGL. Analysis based on all households in the dataset (before applying exclusion criteria). Some households received two installations so have two installation dates.

Figure A.2. Installation dates of RCACs and hot water systems for non-priority households under the EEIS



Notes: Data provided by ActewAGL. Analysis based on all households in the dataset (before applying exclusion criteria). Some households received two installations so have two installation dates.

Appendix B: Comparison of dates of household participation in the EEIS and other energy schemes

Table B.1. Number of days between ActewAGL installations and home visitations via the Home Energy Efficiency Program

Number of days	Visitation before install	Visitation after install
200+	220	133
91-200	122	292
31-90	71	98
1-30	12	4
	Total participants	952

Notes: Data provided by ACT Government, Environment, Planning and Sustainable Development Directorate. The households in the table are public housing tenants only.

Table B.2. Number of days between ActewAGL installations and collection of fridge/freezer in Fridge Buyback scheme

Number of days	Assessment before install	Assessment after install
200+	146	5
91-200	10	6
31-90	9	11
1-30	0	6
0	1	
	Total participants	194

Notes: Data provided by ActewAGL. Analysis based on all households in the dataset (before applying exclusion criteria).

Appendix C: Full results for Tables 3, 5 and 6

Results for an unbalanced panel. The tables present estimated coefficients and standard errors for all variables.

Table C.1. Energy consumption impacts, dependent variables in MJ per quarter

	(1) Natural gas	(2) Grid electricity	(3) Total
Priority households			
$RCAC_{h,q}$	-7,491.91***	1,339.51***	-6,152.40***
	(408.05)	(161.22)	(391.11)
Hot $water_{h,q}$	-7,049.21***	3,208.53***	-3,840.69***
	(934.58)	(522.31)	(816.30)
Non-priority households			
$RCAC_{h,q}$	-6,608.79***	1,373.56***	-5,235.23***
	(698.34)	(232.33)	(685.69)
Hot $water_{h,q}$	-1,795.64	1,114.38*	-681.26
	(1,578.12)	(627.00)	(1,542.46)
Other X vector covariates			
Electric-to-electric $treatment_{h,q}$	6,884.79***	546.88	7,431.67***
	(1,849.17)	(1,647.09)	(1,575.19)
Solar $exports_{h,q}$	-0.26*	-0.78***	-1.05***
	(0.16)	(0.11)	(0.20)
Time-differentiated $tariff_{h,q}$	1,664.10***	309.06	1,973.16***
	(640.31)	(288.61)	(685.38)
$CDDs_{h,q}$	3.23**	7.32***	10.55***
	(1.51)	(0.89)	(1.75)
$HDDs_{h,q}$	8.32***	2.02***	10.34***
	(0.75)	(0.28)	(0.77)
F-tests for priority status	YES	YES	YES
Stat. sig. diff.: RCACs			
Stat. sig. diff.: hot water systems	NO	NO	NO
	(p = 0.27)	(p = 0.90)	(p = 0.24)
Observations	YES	YES	YES
	(p = 0.00)	(p = 0.01)	(p = 0.07)
Households	105,491	105,491	105,491
R-squared	7,098	7,098	7,098
Adj. R-squared	0.83	0.87	0.85

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Table shows full results of Table 3 in manuscript. Exclusion criteria applied (see section 4.2). Total energy consumption excludes self-generation.

Table C.2. Energy consumption impacts, log-transformed MJ per quarter dependent variables

	(1) Log natural gas	(2) Log grid electricity	(3) Log total
Priority households			
RCAC$_{h,q}$	-0.59***	0.18***	-0.28***
	(0.04)	(0.02)	(0.02)
Hot water$_{h,q}$	-0.69***	0.10***	-0.12***
	(0.13)	(0.04)	(0.04)
Non-priority households			
RCAC$_{h,q}$	-0.55***	0.23***	-0.21***
	(0.07)	(0.03)	(0.03)
Hot water$_{h,q}$	-0.57***	0.12	-0.13**
	(0.17)	(0.07)	(0.06)
Other X vector covariates			
Electric-to-electric treatment$_{h,q}$	0.76	0.00	0.29***
	(0.58)	(0.10)	(0.09)
Solar exports$_{h,q}$	-0.00	-0.00***	-0.00***
	(0.00)	(0.00)	(0.00)
Time-differentiated tariff$_{h,q}$	0.11	0.07	0.10**
	(0.09)	(0.05)	(0.05)
CDDs$_{h,q}$	0.00	0.00***	0.00***
	(0.00)	(0.00)	(0.00)
HDDs$_{h,q}$	0.00***	0.00***	0.00***
	(0.00)	(0.00)	(0.00)
F-tests for priority status			
Stat. sig. diff.: RCACs	NO	NO	YES
	(p = 0.59)	(p = 0.18)	(p = 0.06)
Stat. sig. diff.: hot water systems	NO	NO	NO
	(p = 0.57)	(p = 0.84)	(p = 0.89)
Observations	80,370	105,491	105,491
Households	5,340	7,098	7,098
R-squared	0.86	0.85	0.88
Adj. R-squared	0.81	0.80	0.84

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Table shows full results of Table 5 in manuscript. Exclusion criteria applied (see section 4.2). Total energy consumption excludes self-generation.

Table C.3. Greenhouse gas emission impacts, dependent variables in kg CO_2-e per quarter

	(1) Natural gas	(2) Grid electricity	(3) Total
Priority households			
$RCAC_{h,q}$	-386.06***	301.39***	-84.67**
	(21.03)	(36.27)	(36.05)
Hot $water_{h,q}$	-363.25***	721.92***	358.67***
	(48.16)	(117.52)	(102.79)
Non-priority households			
$RCAC_{h,q}$	-340.55***	309.05***	-31.50
	(35.99)	(52.27)	(56.56)
Hot $water_{h,q}$	-92.53	250.74*	158.21
	(81.32)	(141.08)	(143.76)
Other X vector covariates			
Electric-to-electric $treatment_{h,q}$	354.77***	123.05	477.82
	(95.29)	(370.59)	(322.63)
Solar $exports_{h,q}$	-0.01*	-0.18***	-0.19***
	(0.01)	(0.03)	(0.03)
Time-differentiated $tariff_{h,q}$	85.75***	69.54	155.29**
	(33.00)	(64.94)	(70.94)
$CDDs_{h,q}$	0.17**	1.65***	1.81***
	(0.08)	(0.20)	(0.21)
$HDDs_{h,q}$	0.43***	0.45***	0.88***
	(0.04)	(0.06)	(0.07)
F-tests for priority status			
Stat. sig. diff.: RCACs	NO	NO	NO
	(p = 0.27)	(p = 0.90)	(p = 0.43)
Stat. sig. diff.: hot water systems	YES	YES	NO
	(p = 0.00)	(p = 0.01)	(p = 0.25)
Observations	105,491	105,491	105,491
Households	7,098	7,098	7,098
R-squared	0.83	0.87	0.88
Adj. R-squared	0.77	0.83	0.84

Notes: *** p<0.01, ** p<0.05, * p<0.1. All regressions include quarter-by-group fixed effects, and household by quarter-of-year fixed effects. Standard errors are in parentheses. Standard errors are robust and clustered by household. Table shows full results of Table 6 in manuscript. Exclusion criteria applied (see section 4.2).