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Understanding the Key Determinants of Residential Firewood Consumption in Australia: A Nationwide Household Survey

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Abstract: A range of energy sources are used by households across the globe, including electricity, gas, solar, and wood. While there is a large body of international research aimed at understanding household energy use in general, very few studies have focused on the specific topic of residential firewood consumption. In Australia, empirical research to investigate and quantify residential firewood consumption is scarce and outdated, despite the importance of such research for better understanding overall household energy costs and carbon emissions. Unlike other power sources, such as electricity, gas and solar, firewood consumption is not systematically monitored or measured in an objective way, thereby making it difficult to obtain accurate data on the amount of firewood consumed in the residential sector. To address this data gap, the current study used survey data from a sample of 4844 households (including 1168 firewood users) to explore what socio-demographic, dwelling-related and behavioural factors were important for predicting the amount of firewood consumed by Australian households. The results revealed that a range of variables—including geographical location, dwelling type, the number of wood-fired appliances per household, and behavioural factors such as the purpose, timing, frequency, and duration of firewood use—were key determinants of residential firewood consumption in Australia, as self-reported by households. Together, these findings underscore the value of measuring not only geographical and location-based factors in household surveys, but also a range of socio-demographic, dwelling-related, and behavioural variables. By doing so, self-report data collected through surveys is likely to better predict the amount of residential firewood consumption reported (or estimated) by households. Overall, this study makes an important and timely contribution to the literature by demonstrating how social science methods such as household surveys can help improve current estimates of residential firewood consumption used to inform government policy, planning, and decision-making for the future.



Citation: Romanach, L.; Frederiks, E. Understanding the Key Determinants of Residential Firewood Consumption in Australia: A Nationwide Household Survey. *Energies* **2021**, *14*, 6777. <https://doi.org/10.3390/en14206777>

Academic Editor:
Krushna Mahapatra

Received: 24 August 2021

Accepted: 11 October 2021

Published: 18 October 2021

Keywords: firewood; residential energy consumption; wood energy; household energy survey

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1. Introduction

A range of energy sources are used in residential buildings worldwide. In the 2017 to 2018 financial year, electricity was responsible for 46% of the share of residential energy use in Australia, followed by natural gas (36%), wood (11%), solar (4%), and liquefied petroleum gas (LPG; 3%) [1]. While there is a large body of research focused on understanding household energy use in general across Australia and worldwide, very few studies have examined the specific topic of residential firewood consumption, thereby leaving a critical gap in our understanding of overall household energy use.

Identifying the key determinants (or ‘predictors’) of residential firewood consumption and improving current estimates of how much firewood Australian households use is important for multiple reasons—not only to establish the relative impact of different energy sources on household energy costs and carbon emissions, but also to identify opportunities and solutions for reducing such costs and emissions in the future [2,3]. In addition, there are

concerns over firewood appliances being a major source of air pollution, especially in winter months, with the potential for serious negative impacts on human health [4–8]. In turn, a deeper understanding of residential firewood usage could also bring valuable insights to help reduce such health and well-being risks for individuals and communities alike.

A recent review of the international literature has identified a small number of peer-reviewed studies that have examined residential firewood consumption across different parts of the world [9–14]. In Australia, however, published research on the use of firewood as an energy source in the residential sector is scarce and outdated [15], with the most recent nationwide household survey on this topic being more than two decades old [16]. Since Driscoll et al.'s [16] study many years ago, no other published research (to the best of our knowledge) has collected nationwide primary data on residential firewood consumption across Australia. Consequently, estimates of firewood use in Australia's residential sector have tended to rely on outdated data [15,17] or have based their calculations of firewood consumption on broader parameters, such as the number of firewood heaters in Australian dwellings and the number of households per state.

In turn, there is scope to improve the accuracy of these earlier estimates by using more recent primary data and applying a new statistical method that considers a larger number of variables that predict usage of wood-fired appliances. This is particularly important when collecting, analysing, and/or presenting data to inform government policy and planning for the future. For example, in Australia, every year the Federal Government is responsible for publishing the Australian Energy Statistics (AES), which is an official source of energy statistics that details historical energy consumption data (including estimates of residential firewood consumption) and forms the basis of Australia's international reporting obligations. Considering the lack of recent and scientifically rigorous empirical research in this area in Australia, the current study makes an important and timely contribution to the literature by conducting a large nationwide survey to explore the main determinants of residential firewood consumption in households across the country.

When it comes to examining firewood usage among households, one of the key challenges faced by researchers is the ability (or lack thereof) to measure firewood consumption in a scientifically valid, reliable, and objective way. Relatedly, there are limitations in measuring such consumption both longitudinally and at a sufficient level of granularity in order to gain a comprehensive picture of trends in firewood usage over time. Unlike other energy sources, such as electricity, gas, and solar power—all of which are typically connected to energy meters, thereby allowing patterns of consumption to be more easily measured and tracked over time—the use of firewood in Australian households is not systematically measured or monitored in an objective manner. This ultimately makes it difficult to obtain scientifically valid and reliable information on the amount of firewood consumed in the residential sector. To overcome this challenge, researchers across the globe have typically used surveys or interviews to gather data on household firewood consumption [10–14,18–20]. Although similar data collection methods have been used in Australia, it is critically important that information on this topic is updated given that previous research suggests firewood consumption is decreasing over time as wood heaters are replaced by electric and gas heating [21]. In turn, there is an urgent need for more up-to-date insights on the key determinants of firewood consumption in Australia, as well as the overall amount of firewood consumed by households nationwide.

In terms of understanding the key determinants of firewood usage, international research suggests that a combination of factors is important for explaining firewood consumption in the residential sector. More specifically, some of the key determinants of firewood consumption identified in previous research [9,11–14,19] have included geographical location (rural vs. urban areas; colder vs. warmer climate), dwelling type (free-standing houses vs. apartments or units), dwelling age (older vs. newer homes), household size (larger vs. smaller households), age of occupants (older vs. younger head of household) and household income (lower vs. higher incomes). The purpose of firewood use (i.e., whether firewood is used for indoor space heating vs. other domestic activities) and the

availability of other energy sources have also been identified as important factors when investigating firewood use in developing nations (for examples, see [7,8,22]). While this international research is useful for theorising about the likely determinants of residential firewood usage in Australia, the external validity and generalisability of such findings to the nation's local context has not been rigorously tested in recent years. In turn, there is immense value to be gained by conducting further research into this topic in Australia.

Based on the literature, it was predicted that residential firewood consumption would vary across Australia depending on a range of factors. More specifically, we expected that:

- (1) Residential firewood consumption would vary across Australia depending on geographical location (e.g., firewood consumption would be more prevalent in regional areas of the country as opposed to capital cities, as well as in locations with a colder climate);
- (2) Firewood consumption would be associated with a range of household characteristics and dwelling-related variables, such as household size (i.e., number of occupants per dwelling), household income, dwelling age, and dwelling type;
- (3) Firewood consumption would be associated with a number of behavioural variables, such as the number of wood-fired appliances used in the home; the household's main purpose for using firewood; and the timing, frequency, and duration of firewood use; and
- (4) The specific amount or quantity of firewood consumed by Australian households (e.g., tonnes consumed per dwelling each year) would be higher in geographical locations with colder climates.

To test these hypotheses, the current study conducted a nationwide survey of 4844 householders across Australia and explored the following key research questions:

1. How widely is firewood used in Australian households (i.e., prevalence rate) and what is firewood used for?
2. What socio-demographic, household, and dwelling-related characteristics are significantly associated with residential firewood consumption in Australia?
3. How many wood-fired appliances are used by Australian households, when are they typically used, and for how long?
4. Overall, how much firewood is consumed by Australian households on a per dwelling basis each year?
5. What are the main determinants (or predictors) of the total amount of firewood consumed by Australian households?

By answering these five research questions, the current study aimed to achieve one overarching research objective—that is, to obtain a richer and deeper understanding of residential firewood consumption in Australia, specifically in terms of current uptake rates, patterns of household usage, overall consumption levels, and key predictors.

2. Materials and Methods

2.1. Research Design and Procedure

Two electronic surveys (one online and one mobile app-based) were conducted in 2019 to collect self-report data on residential firewood consumption from a large and geographically diverse sample of households across Australia. To be eligible to participate in the surveying, individuals were required to reside in Australia and be at least 18 years old. Across the two surveys, self-report data was collected from a total of 4844 respondents, with just under one-quarter (24%) reporting the use of firewood as an energy/fuel source at home.

Table 1 summarises the key features of each survey and sub-sample. The first survey was administered using a custom-built surveying app, with 770 people across Australia taking part between 1 August and 15 October 2019. Among this sub-sample, the majority of respondents (87%) completed the survey during winter. The second survey was conducted using an online panel provider (I-view Pty Ltd., Sydney, Australia), in an effort to gather

data from a larger and more representative sample, with 4074 people across Australia taking part between 26 September and 6 October 2019. All of these respondents therefore completed the survey during spring.

Table 1. Key features of the study's two surveys.

Survey	1. Mobile App-Based Survey	2. Online Panel Survey
Method/format	Smart device (e.g., mobile phone) app	Online/web-based
Participant sample	Australian adults (aged 18+ years old) who were registered users of a smart device surveying app that allowed participation in short, energy-related surveys over time	Australian adults (aged 18+ years old) who were pre-recruited by an online panel provider and had therefore already registered to participate in paid online surveys
Targets/quotas	No targets were set, as the survey was part of a larger, longitudinal research project that invited Australian adults to download a mobile phone surveying app and participate in short, energy-related surveys over time	Approximately 150 firewood users were targeted per state/territory; however, due to smaller numbers of panel participants in some geographical areas, lower sample size targets were set for three states/territories: Tasmania (n = 110), the Australian Capital Territory (n = 70), and the Northern Territory (n = 20)
Final sample size	770 respondents nationwide, with 210 respondents (27.3%) using firewood at home	4074 respondents nationwide, with 958 respondents (23.5%) using firewood at home
Data collection timeframe	1 August to 15 October 2019, 87% completing the survey during winter	26 September to 6 October 2019, with all completing the survey during spring

The first survey did not specifically target firewood users or set any socio-demographic quotas, as this survey was conducted as part of a larger project that invited everyday Australians to download a surveying app to participate in short, energy-related surveys over time. In contrast, the second survey was purposely designed to recruit around 950 firewood users nationwide in an attempt to ensure that robust, reliable estimates of firewood consumption could be calculated for each Australian state and territory. In the second survey, quotas were also set for selected geographical areas and socio-demographic variables (e.g., state/territory of residence, age, and gender) in order to recruit a sample that was broadly representative of the wider Australian population.

2.2. Sample Representativeness

Self-report data on the residential postcode of survey respondents was used to determine their state or territory of residence. As shown in Table 2, when compared with data from the Australian Bureau of Statistics (ABS) 2016 census, the final combined sample of survey respondents (i.e., both survey one and two) was not fully representative of the broader Australian population in terms of geographical location. This finding was not unexpected, however, because recruitment and sampling targets were set based on the geographical location of respondents in an effort to ensure that a pre-defined minimum number of firewood users were surveyed in each state/territory. This meant that more populated areas of the country (e.g., New South Wales and Victoria) were under-represented in our survey sample, while less populated states and territories (e.g., Australian Capital Territory, South Australia, and Tasmania) were over-represented.

Table 2. Household characteristics of survey sample vs. national census: sample representativeness.

Household Characteristics	All Survey Respondents (n = 4844)	ABS 2016 Census
	Percentage	Percentage
State or territory		
Australian Capital Territory (n = 413)	9	2
New South Wales (n = 949)	20	31
Northern Territory (n = 106)	2	1
Queensland (n = 990)	20	20
South Australia (n = 658)	14	8
Tasmania (n = 330)	7	2
Victoria (n = 780)	16	25
Western Australia (n = 593)	12	11
Not stated (n = 25)	1	
Dwelling type		
Separate house (n = 3655)	75	71
Semi-detached dwelling (n = 452)	9	13
Flat, unit, or apartment (n = 672)	14	14
Other/not stated (n = 65)	1	1
Housing tenure		
Owner-occupied (n = 3632)	75	62
Rented (n = 1090)	23	28
Other/not stated (n = 122)	3	10
Household size		
One person (n = 945)	20	24
Two persons (n = 2241)	46	33
Three or more persons (n = 1624)	34	42
Not stated (n = 34)	1	
Household composition		
Single person household (n = 934)	19	23
Couple with children (n = 1337)	28	30
Couple without children (n = 1840)	38	25
One parent family (n = 326)	7	10
Other/not stated (n = 387)	8	12
Household annual income		
Below AUD 78,000 (n = 2488)	51	47
AUD 78,000 or more (n = 1851)	38	43
Not stated (n = 505)	10	10

In terms of dwelling type, the final combined survey sample had a slightly higher proportion of respondents living in separate houses (75%) and slightly lower proportion living in semi-detached dwellings (9%) compared with the broader Australian population based on ABS 2016 census data (71% and 13%, respectively). However, the proportion of survey respondents who reported living in flats, units, or apartments was relatively similar to that of the broader Australian population (14% each). Home-owners were also slightly over-represented in the survey sample (75%), whereas renters were conversely under-represented (23%), compared with the broader Australian population based on ABS 2016 census data (62% and 28%, respectively).

In addition, the final combined survey sample had a higher proportion of couples without children (38%) compared with the broader Australian population (25%), based on the ABS 2016 census data. Conversely, the proportion of survey respondents who described themselves as lone person households (19%), couples with children (28%), or one parent families with children (7%) was lower than that of the broader Australian population (23%, 30%, and 10%, respectively). Related to household composition, the survey sample had a higher proportion of respondents living in two-person households (47%) compared with the broader Australian population based on the ABS 2016 census data (33%). However, the proportion of survey respondents living in households with one person only (20%)

or three or more persons (34%) was lower than that of the broader population (24% and 42%, respectively).

In terms of household annual income, the survey sample had a slightly higher proportion of respondents with total household incomes under AUD 78,000 per annum (51%) compared with the broader Australian population (47%) based on the ABS 2016 census data.

2.3. Survey Instrument

The survey included various questions about the ownership and usage of wood-fired appliances for domestic purposes, such as space heating (e.g., fireplaces), cooking (e.g., wood-burning ovens, stoves, cooktops, and barbecues) and hot water (e.g., wood-fired water heaters), as well as an open-ended question to estimate total firewood consumption over the preceding 12 months (Please see the supplementary materials for the Survey questions). Self-reported data on standard socio-demographic, household, and dwelling-related characteristics (e.g., household size and type, income, dwelling type, housing tenure, etc.) was also collected from respondents, either by asking these questions in the same survey (for the online panel survey sample) or by sourcing such data from earlier surveys (for the mobile app-based survey sample).

We recognise that this difference in the timing of data collection for the mobile app-based survey sample (that is, sourcing pre-existing data from surveys that householders had completed several months before the wood consumption survey) was not necessarily ideal, as it is possible that some participant characteristics (e.g., household size, composition, annual income, etc.) may change over time. Nevertheless, this design feature was not expected to significantly impact the overall validity of results due to the nature of the data being collected (i.e., self-reported estimates of the amount and timing of firewood consumed in the preceding 12 months).

In Australia, firewood can be sourced in various ways. Within our sample, most firewood consumed by respondents was self-collected (55%), with a reasonable proportion also given for free by others (28%), sourced from private sellers (31%), or obtained from a commercial supplier (33%). As the use of wood as an energy/fuel source is not systematically monitored or measured in an objective manner (i.e., firewood consumption is not 'metered' in the same way as other energy sources like electricity, gas, and solar power), the current research relied on the collection and analysis of self-reported survey data in order to estimate the total amount of firewood consumed by Australian households. Thus, the survey was purposely designed to include several specific questions about the amount, frequency, and duration of wood consumed by respondents' households.

More specifically, the survey asked a single open-ended question about the amount of firewood used by the household in the preceding 12 months. Survey respondents were instructed to provide an estimate of the amount of firewood consumed using whatever metric they were familiar with (e.g., trailer loads, cubic meters, tonnes). To ensure consistency and comparability of responses across the sample, answers to this open-ended question were converted to a standard metric of weight (in tonnes) using some general guiding principles. Specifically, if a respondent answered in terms of volume (e.g., cubic meters), this was converted to tonnes by considering 1 cubic meter of firewood as being equivalent to 0.5 tonnes, in line with previous research [15–17]. If an answer was provided in terms of ute/trailer loads, this was first converted to cubic meters before converting to tonnes. In such cases, if the respondent failed to specify a trailer size, it was treated as a standard 6×4 foot trailer. Table 3 summarises the ute/trailer sizes reported by respondents in the survey, alongside the conversion used to estimated volume (i.e., cubic meters) and weight (i.e., tonnes) for each size.

Table 3. Trailers sizes provided by survey respondents and conversion to cubic meters and tonnes.

Trailer Sizes (in Feet)	Estimated Volume (in Cubic Meters)	Estimated Weight (in Tonnes)
4 × 4	0.45	0.22
6 × 4	0.60	0.33
6 × 8	1.34	0.67
7 × 4	0.78	0.39
7 × 5	0.98	0.49
8 × 4	0.89	0.45
8 × 5	1.11	0.56
8 × 6 (caged)	5.35	2.68
12 × 6	2.01	1.00

It is acknowledged that the current study's method of measuring of firewood consumption only provides a best estimate, namely because self-report data (by its very nature) depends on the recollection and estimation capacity of individual respondents. In turn, the firewood consumption estimates reported herein may be prone to some degree of human error and imprecision. There may also be inaccuracies associated with converting different metrics for firewood to a single, standardised measure or scale. For example, the relationship between weight and volume of wood may vary between different wood species, so converting weight to volume (or vice versa) has some complexities to consider. The current study did not link data on wood species to the quantity of firewood consumed by households (thus making it difficult to assess and correct for any conversation errors); however, it is worth noting that the vast majority (84%) of firewood users reported consuming hardwood timbers rather than softwoods.

Despite the challenges that may arise when collecting and analysing self-report data from surveys, using other (non-survey) measures or criteria to estimate firewood consumption—for example, assessing the number and/or type of wood-fired appliances used by a household—may also be prone to measurement error by failing to take into account the behavioural aspects of firewood consumption (e.g., the timing, frequency, and duration of using wood-fired appliances).

2.4. Analytical Approach

In order to investigate the key research questions and hypotheses outlined earlier, a series of independent cross-tabulations and chi-square tests were conducted to test for statistically significant differences between sub-groups and explore any differences between survey respondents who reported using firewood (herein referred to as “firewood users”) or not using firewood (herein referred to as “non-firewood users”) as a fuel source. Cross-tabulation analyses were also conducted to explore patterns of wood-fired appliance usage (i.e., frequency, timing, and duration) across geographical locations. Together, the results of these cross-tabulations were used to inform a regression analysis to explore and identify the main determinants of the amount of firewood consumed by survey respondents in our sample—that is, to identify what factors explained a statistically significant proportion of the variance in firewood consumption. To conduct the regression, and to remain consistent with previous research [12,14] that has also sought to measure firewood consumption by drawing on household survey data, a left-censored Tobit model was conducted. Given that the majority of Australian households do not use firewood at home, there was a prevalence of zero observations for the dependent variable (i.e., the amount of firewood consumed) in our dataset. The Tobit model uses a maximum likelihood method to estimate the effect of the covariates on the observed outcome and is considered more appropriate than ordinary least squares regression when the dependent variable is censored at zero.

3. Results and Discussion

This section presents the main findings of the nation-wide survey for each of the study's key research questions, as listed earlier in Section 1. First, to understand how widely firewood is used in Australian households and what this firewood is used for, results are presented on the prevalence (i.e., uptake rates) of using firewood as a fuel/energy source in the residential sector. Next, results are presented for the main socio-demographic, household, and dwelling-related characteristics associated with firewood consumption in Australian homes, as well as the number and usage of wood-fired appliances (e.g., timing, frequency, and duration of use). Drawing on the self-report data of survey respondents, estimates for the amount of firewood consumed per annum by Australian households are then presented. Finally, results are presented to demonstrate the main determinants (or predictors) of the self-reported amount of firewood consumed by households per year, specifically after taking into account multiple variables (e.g., geographical, household, dwelling-related, and behavioural factors) when running a regression model.

3.1. How Widely Is Firewood Used in Australian Households and What Is Firewood Used for?

In light of Australia's highly varied climate, it is perhaps unsurprising that the current study found geographical location to be significantly associated with residential firewood consumption. Australia is the world's sixth largest country by total land area, with several different climate zones extending across its various states and territories. Based on climatic data from the Bureau of Meteorology, and taking into account local government areas, the country's National Construction Code (NCC) has identified eight distinct climate zones across Australia: climate zone 1 (high humidity summer and warm winter); climate zone 2 (warm humid summer and mild winter); climate zone 3 (hot dry summer and warm winter); climate zone 4 (hot dry summer and cool winter); climate zone 5 (warm temperate); climate zone 6 (mild temperate); climate zone 7 (cool temperate), and climate zone 8 (alpine). For further details, please refer to: <https://ahd.csiro.au/dashboards/energy-rating/ncc-climates/> (accessed on 16 August 2021).

More specifically, an analysis of the survey data revealed that the proportion of firewood users varied across Australia by state/territory (i.e., location of one's dwelling/ residence), as well as by climate zone. Furthermore, consistent with overseas research [12,14], the self-reported rates of residential firewood consumption among our sample tended to be lower for respondents living in capital cities compared to those living in regional areas (see Figure 1).

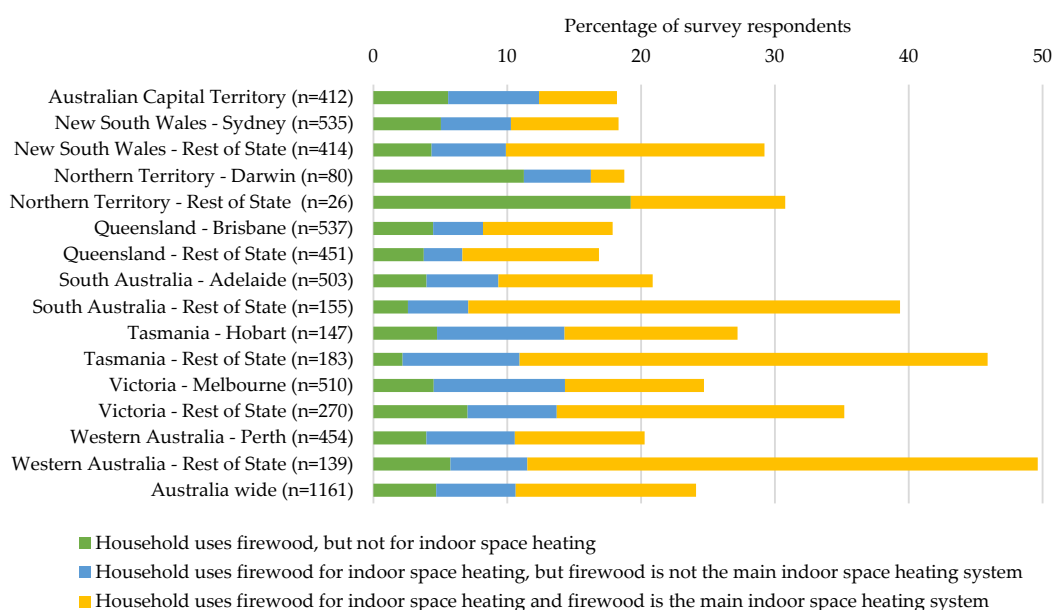


Figure 1. Percentage of survey respondents who reported using firewood in each GCCSA location across Australia.

The survey results also demonstrated the importance of considering the specific purpose(s) of using firewood in Australian homes. For example, participating households reported burning firewood for a range of domestic activities, including space heating (e.g., fireplaces), water heating, and cooking (e.g., wood-fired ovens and barbecues). In our survey sample, the most commonly cited reason for consuming firewood was for indoor space heating, e.g., 81% of firewood users reported using firewood for the specific purpose of indoor space heating. In addition, most firewood users (56%) reported that firewood was the main source of indoor space heating used in their homes. In contrast, much smaller numbers of firewood users reported consuming firewood for other domestic purposes such as outdoor barbecues/pizza ovens (33%), outdoor heating (23%), cooktops and/or ovens (12%), and hot water systems (9%).

Unsurprisingly, the exact proportion of firewood users who reported using firewood for indoor space heating also varied as a function of respondents' geographical location—both in terms of state/territory of residence, or more specifically, Greater Capital City Statistical Area (GCCSA) and climate zone. In terms of the former, the Australian Bureau of Statistics (ABS) define GCCSA as geographical areas that aim to represent or capture the functional extent of each of Australia's eight state and territory capital cities. Within each state or territory, the geographical area or region that is not classified as part of the greater capital city is referred to as "rest of state/territory".

This association between firewood use and geographical location is visually illustrated in Figures 1 and 2, respectively. It is clear from these results that the self-reported use of firewood for indoor space heating was significantly higher in regional areas for all states and territories, except for Queensland and the Northern Territory. In addition, among the sub-sample of respondents who consumed firewood for the specific purpose of indoor space heating, the proportion who reported using firewood as their main source of indoor space heating was also significantly higher in regional areas for all states and territories, except for Queensland and the Northern Territory. These results align with previous research conducted in the state of Victoria, which found that the proportion of households that consumed firewood tends to be higher in regional areas compared to the capital city [23].

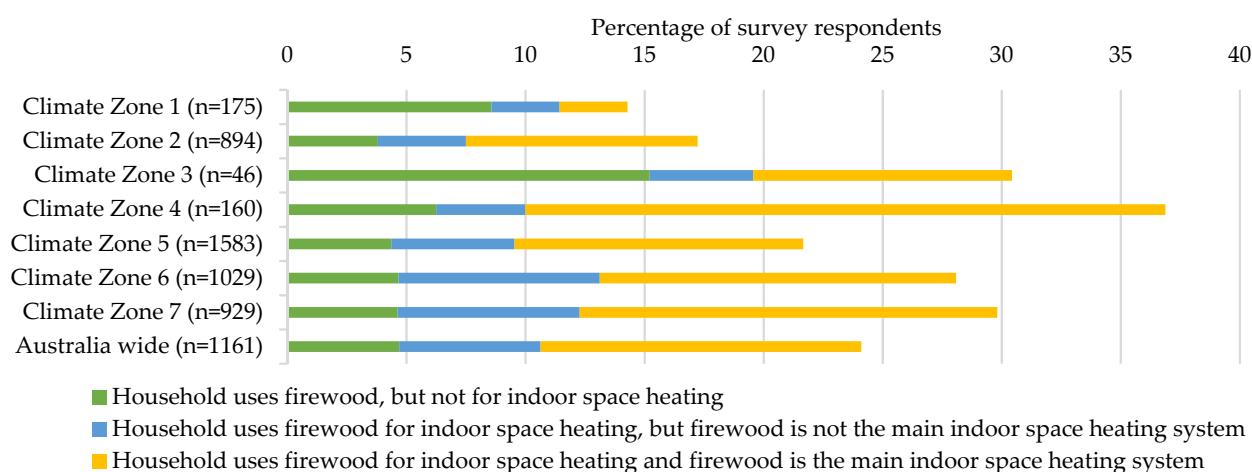


Figure 2. Percentage of survey respondents who reported using firewood in each climate zone across Australia.

In terms of climate zone, the use of firewood for indoor space heating was significantly lower in climate zones with warmer winters (e.g., climate zones 1 and 2, which are characterised by warm winters) and higher in climate zones with cooler winter (e.g., climate zone 4, which is characterised by cool winter, and climate zone 6 and 7, which are characterised as mild and cool temperate, respectively).

3.2. What Socio-Demographic, Household, and Dwelling-Related Characteristics Are Significantly Associated with Firewood Consumption in Australia?

Across the entire sample of Australian households that were surveyed as part of the current research, approximately one-quarter (24%) reported using firewood as an energy source at home. As presented in Table 4, certain socio-demographic, household and dwelling-related factors were found to explain a statistically significant proportion of the variability in firewood consumption among this sample. Consistent with previous research [12,14], the firewood users in our sample were more likely to report living in separate houses (vs. semi-detached dwellings or units/apartments), in older homes (e.g., homes constructed before vs. after 2000), and in owner-occupied (vs. rented) dwellings. In addition, firewood users were more likely to live in larger households (e.g., three or more occupants vs. one or two occupants) and have higher levels of annual household income (e.g., AUD 78,000 or more per year vs. less than AUD 78,000 per year). They were also more likely to describe themselves as family households with children (vs. single or couple-only households) and more likely to use bottled gas and/or solar electricity as energy sources at home (vs. mains gas and/or only electricity).

Table 4. Household characteristics of survey sample: firewood users vs. non-firewood users.

Household Characteristics	Household Uses Firewood (n = 1168)	Household Does Not Use Firewood (n = 3676)	All Survey Respondents (n = 4844)	Statistically Significant Difference between Firewood and Non-Firewood Users
	Percentage	Percentage	Percentage	
Dwelling type				$\chi^2(3) = 188.71; p < 0.001$
Separate house (n = 3655)	90	71	75	
Semi-detached dwelling (n = 452)	4	11	9	
Flat, unit, or apartment (n = 672)	5	17	14	
Other/not stated (n = 65)	1	1	1	
Dwelling age				$\chi^2(2) = 60.25; p < 0.001$
Prior to 2000 (n = 3098)	73	61	64	
Since 2000 (n = 1366)	22	30	28	
Do not know/not stated (n = 380)	5	9	8	
Housing tenure				$\chi^2(2) = 34.96; p < 0.001$
Owner-occupied (n = 3632)	82	73	75	
Rented (n = 1090)	17	24	23	
Other/not stated (n = 122)	2	3	3	
Household size				$\chi^2(3) = 156.03; p < 0.001$
One person (n = 945)	11	22	20	
Two persons (n = 2241)	42	48	46	
Three or more persons (n = 1624)	47	29	34	
Not stated (n = 34)	1	1	1	
Household composition				$\chi^2(3) = 35.30; p < 0.001$
Single person household (n = 934)	11	22	19	
Couple with children (n = 1337)	38	24	28	
Couple without children (n = 1840)	34	39	38	
Other/not stated (n = 733)	17	15	15	
Household annual income				$\chi^2(2) = 45.50; p < 0.001$
Below AUD 78,000 (n = 2488)	46	53	51	
AUD 78,000 or more (n = 1851)	46	36	38	
Not stated (n = 505)	8	11	10	
Household energy sources				
Mains gas (n = 2299)	41	49	47	$\chi^2(2) = 23.13; p < 0.001$
Bottled gas/LPG (n = 973)	33	16	20	$\chi^2(2) = 154.81; p < 0.001$
Solar (n = 1834)	46	35	38	$\chi^2(2) = 40.42; p < 0.001$

3.3. How Many Wood-Fired Appliances Are Used by Australian Households, When Are They Used, and for How Long?

Among the sample of survey respondents, most firewood users reported having one wood-fired appliance (64%), with 24% reporting two appliances, and 11% reporting three or more appliances. For the remaining 1% of firewood users, the number of wood-fired appliances was not stated. As previously mentioned, results also revealed that among the sub-sample of survey respondents who used firewood as an energy source, 81% reported using firewood for indoor space heating and 56% stated that firewood heating was their main type of home heating. These findings underscore the importance of exploring patterns of firewood use for indoor space heating from a behavioural perspective (i.e., frequency, timing, and duration of firewood usage).

In terms of timing, as shown in Figure 3, the use of firewood for indoor space heating among the sample of survey respondents was consistent with previous research conducted in Australia [5], which found that firewood consumption was most common during the cooler months of the year, particularly May to September (peaking in July during the winter period). Research conducted in Nepal has also found that the consumption of firewood tends to be higher during the winter months [8]. In addition, as shown in Figures 3–5, the self-reported timing (i.e., months in the year), frequency (i.e., days per week), and duration (i.e., hours per day) of firewood consumption differed across geographical locations. For example, firewood users who consumed firewood for space heating and lived in a colder climate (e.g., Tasmania and/or climate zones 4 and 7) tended to report using firewood for longer periods throughout the calendar year (Figure 3), as well as for more days per week and more hours per day, compared to those living in locations with warmer climates (e.g., Queensland and the Northern Territory and/or climate zones 1 and 2; Figures 4 and 5).

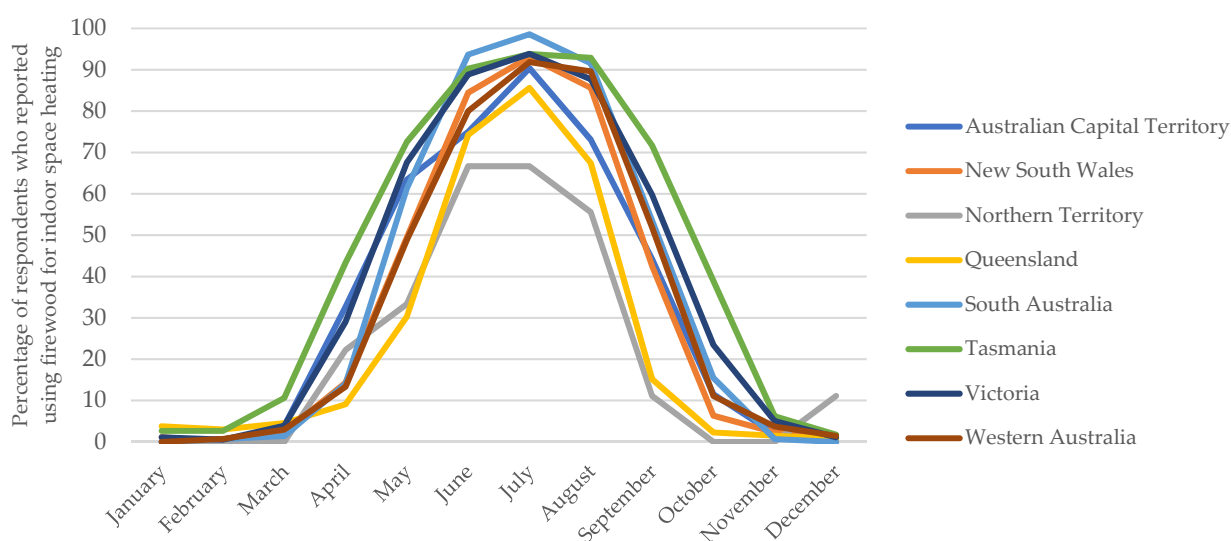


Figure 3. Use of firewood for indoor space heating across different months of the year (n = 936).

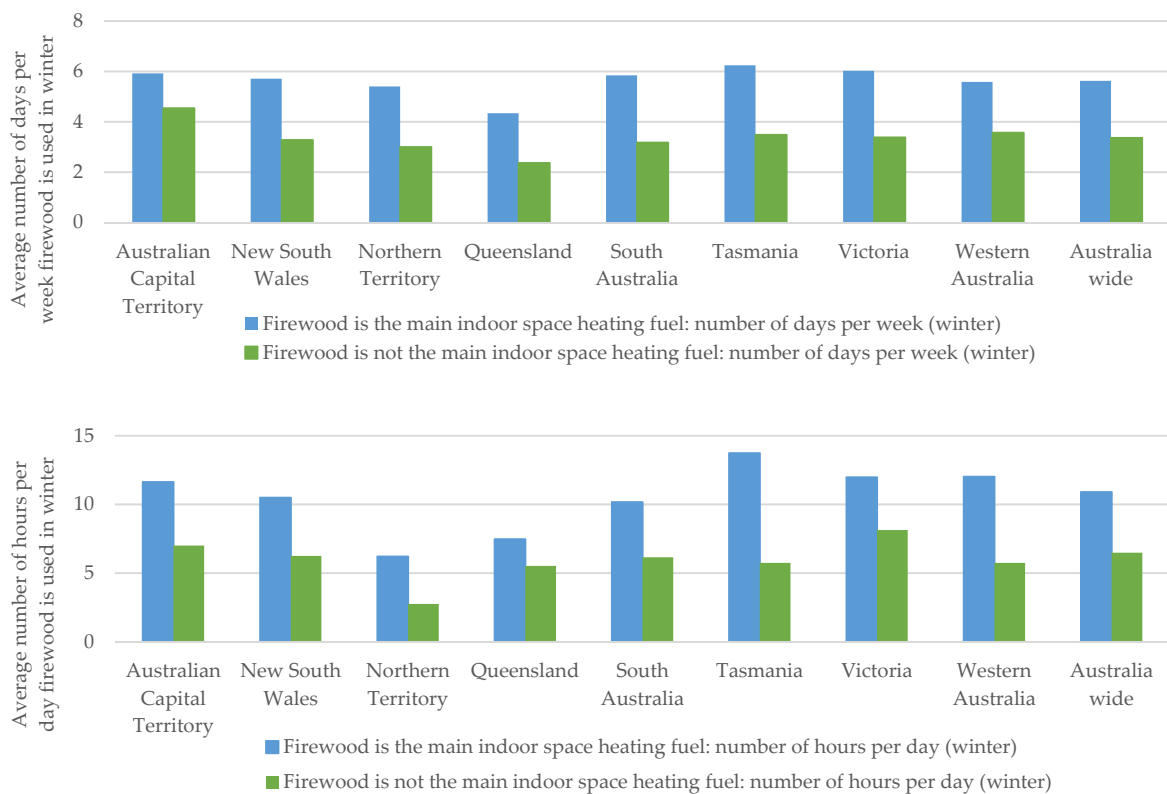


Figure 4. Frequency and duration of firewood use for indoor space heating for each state or territory (n~937).

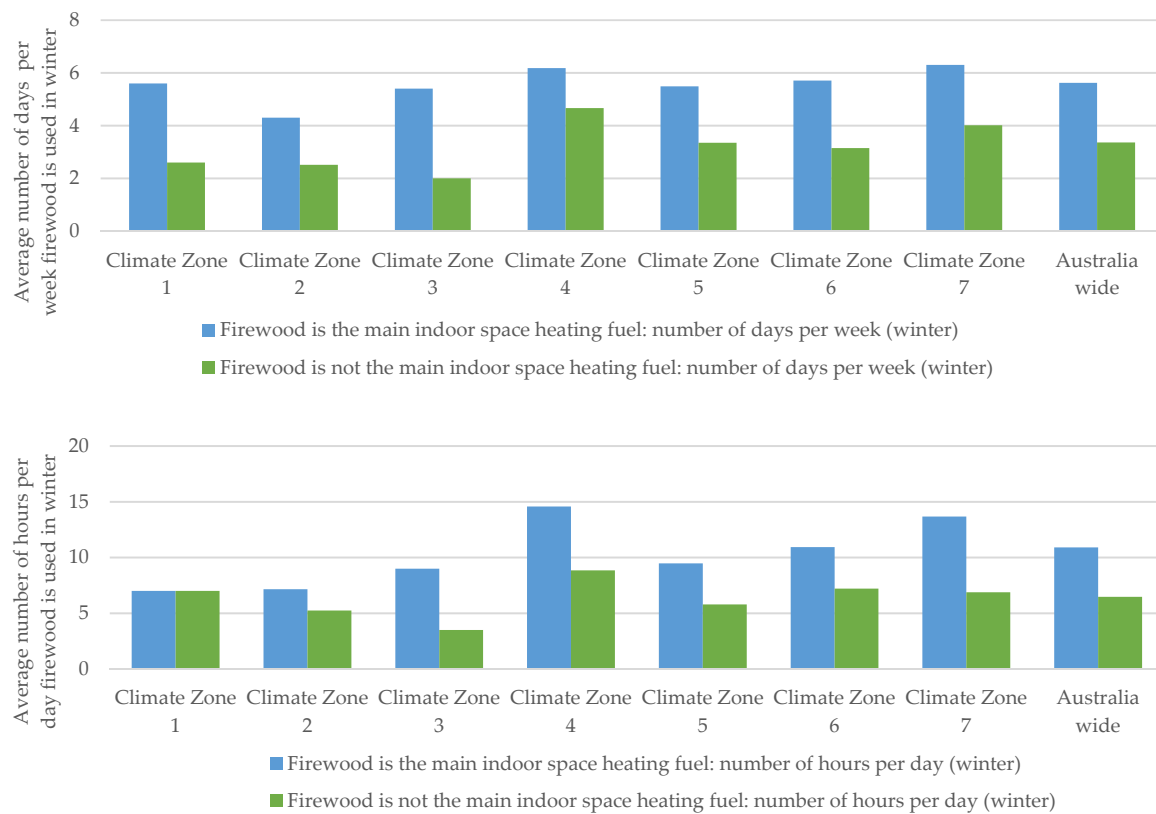


Figure 5. Frequency and duration of firewood use for indoor space heating for each climate zone (n~935).

In addition, firewood users who reported using wood as their main energy/fuel source of indoor space heating also tended to report consuming firewood for more days per week, as well as more hours per day, compared to firewood users who did not use wood as their main energy/fuel source of indoor space heating (see Figures 4 and 5).

3.4. How Much Firewood Is Consumed by Australian Households?

Among the sub-sample of firewood users, about six-in-seven respondents (86%; $n = 1008$) provided an estimate of the amount of firewood consumed by their household over the 12 months preceding the survey. In this group, about two-thirds (65%) reported using between 0.5 and 5.0 tonnes of firewood in the 12 months before the survey. Just under one-quarter (23%) reported using less than half a tonne, with the remaining respondents (12%) reporting that they used 5.0 tonnes or more.

As shown in Figures 6 and 7, the amount of firewood used in the past 12 months again varied depending on the geographical location of respondents and whether or not firewood was used by the household as the main energy/fuel source for indoor space heating. It should be noted that the regression analysis identified 22 responses as outliers. To improve the reliability of the data, these outliers were removed when reporting the average amount of firewood consumed per household each year. Our results from the regression analysis revealed that aligned with previous research conducted in Nepal [22], which also found that firewood consumption was higher when used for indoor space heating and/or in a colder climate.

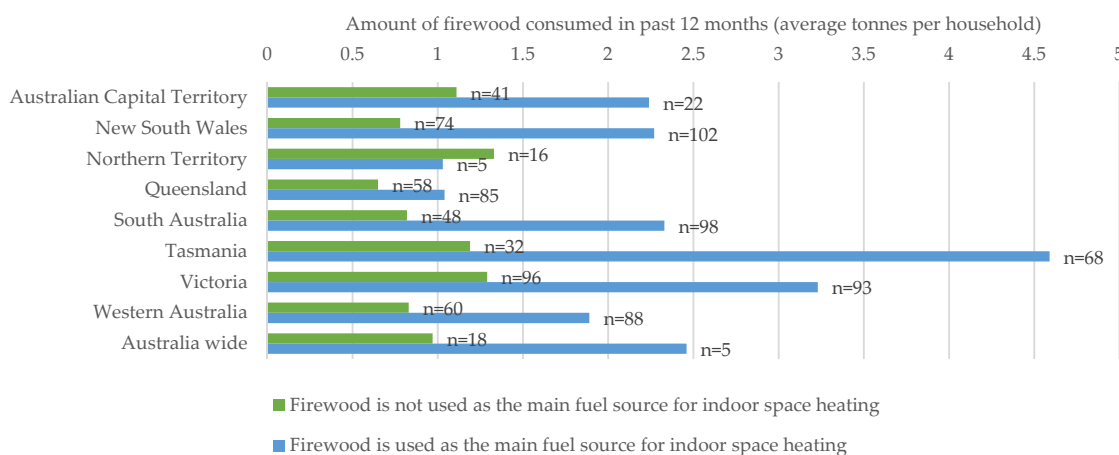


Figure 6. Average amount of firewood consumed per household in the past 12 months in each Australian state and territory ($n = 986$).

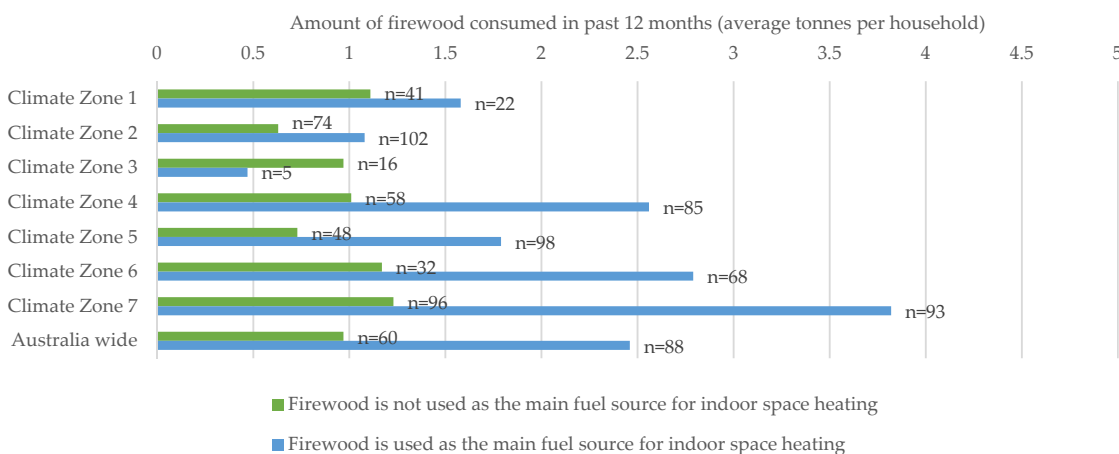


Figure 7. Average amount of firewood consumed per household in the past 12 months in each climate zone ($n = 986$).

3.5. What Are the Main Determinants of the Total Amount of Firewood Consumed by Australian Households per Annum?

As described earlier in Section 2.4, a left-censored Tobit model was conducted to explore how the key variables identified in the cross-tabulation analyses were associated with the overall amount of firewood consumption reported by survey respondents.

As shown in Table 5, this analysis involved running three models:

Table 5. Results of the Tobit models to investigate the key determinants of the total amount of firewood consumed per household each year in Australia.

Self-reported amount of Firewood Consumed by Household (Tonnes; Past 12 Months)	Model 1		Model 2		Model 3	
State or Territory (baseline = Tasmania)						
Australian Capital Territory	−1.99 ***	(0.36)	−0.91 **	(0.33)	−0.71 **	(0.26)
Northern Territory	−0.30	(0.43)	0.22	(0.38)	−0.53	(0.31)
New South Wales	2.28 *	(0.91)	1.41	(0.87)	0.13	(0.65)
Queensland	0.31	(0.62)	−0.12	(0.53)	−0.98 *	(0.43)
South Australia	0.64	(0.46)	0.61	(0.40)	−0.65	(0.33)
Victoria	−0.21	(0.39)	0.83 *	(0.35)	−0.15	(0.28)
Western Australia	0.98 *	(0.48)	0.94 *	(0.42)	−0.70 *	(0.35)
Climate zone (baseline = climate zone 7)						
Climate zone 1	−4.43 ***	(0.79)	−3.10 ***	(0.76)	−0.17	(0.58)
Climate zone 2	−3.09 ***	(0.59)	−1.91 ***	(0.51)	−0.05	(0.41)
Climate zone 3	−3.06 ***	(0.87)	−2.52 **	(0.79)	0.22	(0.61)
Climate zone 4	−1.08 *	(0.47)	−1.07 **	(0.41)	−0.06	(0.34)
Climate zone 5	−2.37 ***	(0.40)	−1.50 ***	(0.36)	−0.24	(0.29)
Climate zone 6	−1.03 **	(0.35)	−1.00 ***	(0.30)	−0.21	(0.25)
Geographical location: capital city	−1.06 ***	(0.16)	−0.39 *	(0.16)	−0.01	(0.13)
Dwelling characteristics						
Dwelling type: separate house			1.52 ***	(0.22)	0.58 ***	(0.17)
Dwelling age: built prior to year 2000			0.56 ***	(0.15)	0.08	(0.12)
Energy source: dwelling has mains gas connection			−1.32 ***	(0.16)	−0.21	(0.13)
Household characteristics						
Housing tenure: owner-occupied			0.28	(0.18)	−0.04	(0.14)
Household size (number of occupants)			0.04	(0.06)	0.03	(0.05)
Household composition: couple with children			0.23	(0.16)	0.22	(0.13)
Household annual income			0.00	(0.00)	−0.00	(0.00)
Usage of wood-fired appliances and firewood						
Number of wood-fired appliances			2.38 ***	(0.08)	1.05 ***	(0.06)
Firewood is main fuel source for indoor space heating					0.41 *	(0.19)
Timing of using firewood for indoor space heating (months per year)					0.34 ***	(0.04)
Frequency of using firewood for indoor space heating in winter (days/week)					0.19 ***	(0.04)
Duration of using firewood for indoor space heating in winter (hours/days)					0.09 ***	(0.01)
Constant	−0.48	(0.25)	−3.93 ***	(0.36)	−3.08 ***	(0.28)
Scale/sigma	11.69 ***	(0.60)	6.13 ***	(0.31)	3.44 ***	(0.17)
Total number of observations	4641		3845		3845	
Uncensored observations	986		877		877	

Note: Standard errors in parentheses; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Model 1 included variables related to the survey respondent's geographical location, namely: state/territory of residence, climate zone, and whether or not the respondent lived in a state/territory capital city (mapped using ABS GCCSA region categories).

Model 2 included the same variables as Model 1, alongside selected socio-demographic and household variables (e.g., household size, composition, income, housing tenure) and

dwelling-related features (e.g., dwelling type and age, presence of a mains gas connection, number of firewood appliances).

Model 3 included the same variables as Model 2, alongside selected behavioural variables (e.g., whether firewood was the main energy/fuel source used by the household for indoor space heating, number of months per year firewood was used for indoor space heating, and the average number of days per week (i.e., frequency) and hours per day (i.e., duration) firewood was used for indoor space heating in the winter).

The results of these analyses revealed that when a mix of socio-demographic, dwelling-related, and behavioural variables were simultaneously included in the model, the variables that remained statistically significant ($p < 0.05$) included: state/territory of residence, whether or not the respondent lived in a separate house, the number of wood-fired appliances used by the household, whether or not firewood was the main energy/fuel source of indoor space heating, the timing of firewood use (i.e., number of months per year firewood was used for indoor space heating), and the frequency and duration of firewood used for the specific purpose of indoor space heating (i.e., number of days per week and hours per day) in winter.

As reported in Section 3.1, the proportion of firewood users was higher in those climate zones across Australia with cooler winter periods (e.g., climate zone 4, which is characterised by cool winters; and climate zones 6 and 7, which are characterised as mild temperate and cool temperate, respectively). Overall, these findings demonstrate the value of measuring not only geographical and location-based factors when investigating residential firewood consumption, but also a range of socio-demographic, dwelling, and behavioural variables associated with households. By doing so, data collected through survey-based research is likely to better predict the patterns of residential firewood consumption self-reported by households.

4. Overall Discussion

4.1. Summary of Key Findings

The key findings of this study shed new light on residential firewood consumption—and household energy use more generally—by both broadening and deepening our understanding of how firewood is used as a fuel source in Australian households. Several results arising from this study are of noteworthy importance to the energy sector, not only theoretically and empirically, but also in terms of practical implications. First, the results of this study demonstrate that it is very important to consider a household's geographical location when it comes to investigating and estimating residential firewood consumption in Australia. The current research found that factors such as state/territory of residence, climate zone, and whether one's dwelling is located in a capital city or regional area are important predictors of residential firewood use—not only in terms of the proportion of households who use firewood as a fuel source and the amount of firewood consumed per year, but also in terms of the proportion of households who use firewood as their main source of energy for the specific purpose of indoor space heating. Consistent with previous research [12,14,23], self-reported levels of firewood consumption in our survey sample tended to be lower for respondents living in capital cities compared to those living in regional areas. In addition, the estimated amount of firewood consumed per household in the 12 months preceding the survey (as self-reported by survey respondents) tended to vary across geographical locations when firewood was the household's main energy/fuel source for indoor space heating. In general, those living in cooler climates (e.g., Tasmania and/or climate zone 7) tended to report higher levels of firewood usage compared to those living in warmer climates (e.g., Queensland, the Northern Territory and/or climate zones 2 and 3).

In addition to the important factor of one's geographical location, the current study also demonstrated the importance of considering some key household and dwelling-related characteristics when estimating the proportion of households who use firewood—a finding that aligns with previous research [12,14]. Specifically, when geographical location

and dwelling-related characteristics were considered simultaneously, the results revealed several key determinants of the amount of firewood used by a household, including variables such as dwelling type, dwelling age, energy sources used by the household, and the number of wood-fired appliances. In particular, the results suggested that living in a separate house (vs. semi-detached dwelling or unit/apartment), in an older home (e.g., dwellings built before vs. after 2000), and/or using bottled gas and/or solar electricity as energy sources at home (vs. using mains gas and/or only electricity) were all associated with greater amounts of firewood consumption.

Moreover, the current study also demonstrated that collecting and analysing self-report data on behavioural factors—namely patterns of using wood-fired appliances—can further improve estimates of residential firewood consumption. Specifically, factors such as whether or not firewood was used by the household as the main energy/fuel source for indoor space heating, as well as the timing (i.e., number of months per year), frequency (i.e., number of days per week), and duration (i.e., number of hours per day) of using firewood for indoor space heating, were found to be statistically significant determinants of the amount of firewood consumed per household in the past 12 months. Overall, these findings demonstrate that measuring not only geographical and location-based factors in survey-based research, but also a range of socio-demographic, dwelling, and behavioural variables is likely to better predict the amount of firewood consumed by Australian households.

4.2. Limitations and Directions for Future Research

While the current research makes an important, timely, and novel contribution to the existing literature on residential firewood consumption, both in Australia and overseas, in this section we outline some of the study's limitations and identify several avenues for future research in order to improve data collection, sample representativeness, and the generalisability of results.

First, it is important to highlight that sampling error and self-selection bias may have impacted the results of the current study. As both surveys were conducted digitally (e.g., via a smart device app or online), the sample of participating households was restricted to those individuals who had access to computers, mobile devices, and the internet. In addition, the sample was limited to people who had previously signed-up (e.g., registered users) to the relevant mobile phone app or online survey panel, thereby excluding some segments of the wider Australian population. In turn, there was a risk that the types of people who agreed to take part in the surveys may have systematically differed in key characteristics (e.g., attitudes, interests, values, beliefs, behaviours etc.) from those who refused to participate, or from those who were not invited to participate in the first place. Despite this potential drawback, the use of online and app-based surveying was still considered to be the most efficient, practical, and cost-effective way of recruiting, sampling, screening, and collecting data from a large sample of households for the current research. To address this limitation in future studies, researchers could aim to survey a broader cross-section of the Australian community by employing multiple methods and modes for participant recruitment, such as postal, telephone, or even face-to-face surveying. Drawing on multiple or mixed-methods is likely to prove useful for expanding the potential pool of survey respondents to include those households who do not have access to mobile devices and the internet, or who are hard to reach for other reasons (e.g., low-income and/or minority groups who may be under-represented in survey-based research).

In addition, the surveys conducted for the current study were both cross-sectional nature; that is, self-report data was collected from respondents at one period in time, during a few months in the latter half of 2019. Longitudinal data collection (i.e., collecting data from the same household repeatedly over time) would also be a fruitful avenue for future research as it would allow for a more in-depth investigation of potential temporal changes in firewood usage, e.g., observing how patterns of firewood consumption vary from month-to-month, year-to-year, and beyond. In addition, there may be value in exploring whether there is an optimal frequency or duration of assessing residential firewood consumption

(e.g., daily, weekly, monthly, seasonally, yearly, etc.) in order to minimise respondents' memory errors and/or recollection bias, as this could also improve self-reported estimates of residential firewood consumption. More frequent surveying may also have the benefit of allowing more fine-grained data collection over time (i.e., measuring the frequency and duration of firewood use at different times of the year, such as how many hours per day and/or days per week firewood is used across the various seasons).

Future research may also benefit by identifying new and improved (i.e., more objective, accurate, and precise) measurement methods, tools, or criteria for residential firewood consumption. In the current study, survey respondents were asked to self-report the amount of firewood consumed by their household using a range of metrics. While our use of a simple open-ended survey question to collect such data had the advantage of allowing householders to respond using whatever measurement metric they preferred or understood best, there may be scope to further strengthen or refine this measurement approach. For example, developing more specific guidelines or instructions that help householders to accurately identify and report different wood species used for residential firewood, as well as more precise methods for converting between volume and weight for each species, could help to minimise the risk of measurement error, self-report biases, or other inaccuracies in retrospective reporting. Future studies could also consider implementing weight survey methodologies similar to those used in other international studies (for an example from Nepal, see [8,24]), where the weight of a firewood bundle is measured before and after firewood was burned. In addition, if the intention is to record and track firewood over an extended period (i.e., more longitudinal or repeated measures research), study participants could potentially use the weight survey method to keep a diary or written record of the amount of firewood consumed over a specific timeframe (e.g., during winter months).

Finally, future research could also explore opportunities for linking objectively measured weather data—such as daily temperature and heating degree days (HDDs)—with longitudinal self-report data on firewood use, particularly if such data is collected over a specific timeframe (e.g., past day or week) or across different seasons of the year (e.g., winter vs. summer). This type of analysis may enable an empirical investigation of the potential impact of temperature and HDD variation (if present) on firewood consumption, both between and within different Australian states and territories.

5. Conclusions

The current research collected and analysed self-reported survey data from a large sample of Australian households to better understand the key characteristics of firewood vs. non-firewood users, the primary drivers of residential wood consumption, and the typical patterns and behaviours associated with differences in firewood use between households (e.g., timing, frequency and duration of wood consumption). Better understanding the key determinants of firewood consumption represents an important step towards improving the accuracy and robustness of firewood estimates in Australia. There are multiple avenues for future research and analysis that may further strengthen the scientific validity, reliability, and generalisability of results presented in this paper. We encourage more studies in this area so as to build a more comprehensive and complete picture of residential firewood consumption in Australia.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/en14206777/s1>.

Author Contributions: Research conceptualization and methodology—L.R. and E.F.; research data analysis—L.R.; manuscript conceptualisation and writing—L.R. and E.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted as part of the National Energy Analytics Research (NEAR) Program, with funding from the Australian Government's Department of Industry, Science, Energy and Resources.

Institutional Review Board Statement: The study was conducted in accordance with Australia’s Privacy Act 1988 (Cth) and the National Health and Medical Research Council’s National Statement on Ethical Conduct in Human Research (2007)—Updated 2018. It was also approved by the Commonwealth Scientific and Industrial Research Organisation’s (CSIRO) Social Science Human Research Ethics Committee (protocol 130/19 approved on 11 September 2019).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The research data is not publicly available due to ethical clearance and privacy restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

Research Ethics: All participants gave their informed consent before they participated in the study. This study was conducted in accordance with the Australian National Statement on Ethical Conduct in Human Research (2007)—Updated 2018, and the protocol was approved by CSIRO’s Social Science Human Research Ethics Committee.

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