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Hybridization and accumulation of space-heating systems in Finnish detached housing

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ABSTRACT

The uptake of renewable energy sources is intensifying in detached houses in the Nordic countries. Survey results (N = 4276) among a detached-house owner association members in Finland imply that the energy transition has progressed further than believed. In the sample, 89 % of households had two or more systems which suggests an accumulation and parallel use of heating systems instead of removing older energy technologies. The phenomenon concerns houses with electric heating, wood heating and air-source heat-pumps, and the owner-occupant sample is rather even across socio-demographic backgrounds. However, larger homes had a higher number of energy technologies, and hybrid arrangements were also adopted more by male respondents. Women, unemployed, and families with three members or more had higher odds for relying only on one energy technology or fuel. The results call for urgent updates in European energy statistics and classifications and the energy policy measures targeted at residential sector, both from energy justice and heating decarbonization perspectives. This is one of the rare studies focusing on hybridization of residential heating in Nordic countries.

1. Introduction

The uptake of renewable energy sources is intensifying on all scales from large industrial installations to small scale plants in detached houses [1]. Many homeowners are adopting small-scale renewable energy technologies (S-RET)[1] both as primary and supplementary heating sources [2]. The uptake of S-RET has been thus far examined largely in terms of substitution of older fossil fuel based or direct electric heating (e.g. Refs. [1,3]), even as research has for long pointed that consumers perceive their extant and novel energy systems as complementary to each other, not only competing (e.g. Refs. [4–6]). This may result not only in adding supplementary S-RETs to extant systems or replacing them as primary heating sources, but also in 'hybrid' systems, in which several S-RETs are combined for the energy needs of the same house. We define such hybrids as heating arrangements comprised of combinations of two or more energy technologies, the use of which alternates based on seasonal or daily cycles utilizing the perceived value points of each individual system within these changing conditions (in contrast to e.g. heating systems where there is a primary heating system and its supplements).

The hybrid heating phenomenon is poorly characterized in research and deserves attention. The research that has been undertaken observes that hybrid solutions have wide technical variety, occur in diverse socio-economic contexts, and contribute to several different low carbon pathways in detached housing stock. Thoroughgoing hybrid solutions provide trailblazing exemplars of energy positive and very low energy housing. They can help address energy poverty [7], and increase energy security [8,9]. They can generate more flexible energy practices [10], provide more resilient heating systems, and help flatten peak demand [11,12]. Hybrid solutions are purposefully planned for new build houses but can also evolve through energy renovations or inclusions of additional heating sources to an existing heating system [2]. The latter alternative can lead to pathways of subsequent additions, typically responding to different seasonal, economic, and operational opportunities and household conditions [10,13].

Despite the EU's ambitious plans to decarbonize the building sector [3,14], hybrid heating solutions are absent in policy considerations [15], and from residential heating statistics. Much research also builds on distinct positions of heating systems (e.g. Ref. [16]). European heating statistics are based on a division between primary and supplementary heating systems, where 'primary' denotes a system that

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[1] S-RET includes solar photovoltaic panels (Solar PV, PV), solar thermal collectors (Solar collectors), ground source heat pumps (GSHP), Air source heat pumps (ASHP), Air to water heat pumps (ASWHP), Exhaust air heat pumps (EAHP), micro-wind power (Wind), pellet and woodchip burning furnaces (Pellets) and solid wood fireplaces that reserve heat (Wood).

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Abbreviations

ASHP	Air source heat pump
AWSHP	Air-to-water source heat pump
EAHP	Exhaust air heat pump
GSHP	Ground source heat pump
GJ	Giga-joule
GWh	Giga-watt-hour
PV	Solar photovoltaic panel
S-RET	Small-scale renewable energy technology

'provides most of the heat to the dwelling', and 'supplementary' a system that 'is used less often' [17]. The same applies to national statistics (e.g. Refs. [18–20]). If an increasing number of houses are heated with hybrids that build on complementary value-points, these statistics listing only one supplementary system and insisting on a hierarchy between systems may provide an erroneous view of the reality of home heating. They peripheralize more complex heating arrangements and, for instance, exaggerate the dependencies that households may have on any one heating source. To gain a better sense of the progress in user-end energy transition, we conducted an energy related survey in Finland in the autumn of 2022. The survey targeted detached and semi-detached housing which is home to around half (47 %) of Finnish people [21] and earlier studies have reported an emergence of heating hybridization in detached housing [2,13,22,23]. Other housing forms are terraced houses (13 % of population [21]) and apartments (38 %) where opportunities for heating system transition are essentially different due to their collective ownership and decision-making structures and location in townships typically served by district heating networks.

Our main research questions are.

1. what types of energy producing combinations and arrangements do detached houses use at this point of energy transition?
2. is hybridization in heating inclined to certain types of buildings or socio-demographic background of households?
3. does the development of hybrid heating indicate need for changes in energy policy measures?

The paper is structured as follows. In the following section we outline literatures on S-RET adoption and classification systems. In section 3, we describe our research context, research process, data and methods and proceed to present the results and discussion of the study in section 4. We conclude with policy implications. Overall, our results corroborate existing findings that the energy transition is advancing well in the Finnish residential sector. Yet it provides new insights on the progress of the transition and its highly contingent character. Our analysis points to the need to update the ways in which data about household heating is collected and classified. These issues have also direct implications for policy regarding energy subsidies and promotion of renewables among citizens.

2. Background

2.1. S-RET adoption and diffusion

As energy transitions progress, it has become timely to analyse the diffusion of key technologies in different countries, scales and contexts. Most analyses focus on aggregated deployment of particular renewable technologies, such as wind and solar PV (e.g. Refs. [24–27]). Studies have further focused on the early phases of uptake and how entrant technologies become gradually institutionalized and embedded in citizen's everyday consumption, facilitating their wider spreading (e.g. Refs. [23,28–30]). In turn, studies on energy transitions follow the advancement of particular renewables as a "technology substitution processes where a novel technology emerges in a niche, improves and diffuses over time and eventually replaces or integrates with an established technology" [31]. Where the complementarities and competition in the diffusion of different renewables are studied, this takes place at the sectoral level, leaving technology complementarities at points-of-use without explicit attention [32]. This is likely due to lack of available data because the way energy adoption statistics are gathered do not make it readily available (see Section 2.3).

Some studies [6,23] differentiate S-RET diffusion on different scales of deployment and other studies have provided insights into the adoption of particular energy technologies in detached housing, such as heat pumps [33]. Here, the key finding is that S-RET diffusion across countries is highly uneven both in terms of market penetration levels and the extents of different renewables [6,23,33], which, in the EU, is not explainable by geography or available support schemes [34] only. Rather, existing literatures point to the influence of various factors stretching from the household to the national level, highlighting the complexity and situatedness of S-RET adoption [6,12,35].

2.2. Contingencies of S-RET adoption

On the national level, markets and policies are crucial for the diffusion of S-RET. Markets develop in relation to existing infrastructures [36], institutions and macro-economics [37]. While they develop slowly, the maturity of markets influences the ability of adopters to operate in the market [38]. Market conditions, together with advocacy or rejection of S-RET by social movements, professional communities, and the mass media, can influence the legitimacy of S-RET [6]. Similarly, cultural [22] and climatic conditions [23] influence S-RET adoption and diffusion. Policies, like financial incentives, are generally considered important in the diffusion of S-RET and are available in many European countries [12]. Yet, it has been suggested that financial incentives alone can be ineffective [35], as focus on them easily obscures the importance of policy trajectories and broader policy palettes including, for instance, the training and certification of qualified installers [6], which positively influence the diffusion of S-RET.

On the local level the importance of peer and social network effects for S-RET adoption has been observed by several authors. Graziano and Gillingham [39], for instance, note that localized neighbourhood effects are stronger drivers for solar PV adoption than socio-economic factors. Others have noted that S-RET adopters often influence their peers [40–42] and are keen to inform others about the benefits of S-RETs [43]. The availability and expertise of local companies and installers [11,44] are important factors for S-RET diffusion. While de-localized online peer communities can be crucial in market creation and adoption of S-RET too [45,46].

Finally, on the household level the influence of socio-demographic factors (e.g., education, age, income, values) on S-RET adoption consideration and decisions is often cited (e.g. Refs. [43,47]), although their influence is not necessarily straightforward [40,48] or uniform across different S-RET [35]. Instead, socio-demographic characteristics entwine with other household level factors. Detached house dwellers and homeowners tend to be more likely to adopt S-RET than renters and apartment dwellers [35,49]. In turn, in line with general diffusion theory [50], early adopters are more guided by interest in technology or environmental issues and are more likely to adopt innovative solutions, in comparison to later adopters that are more motivated by economic benefits [51]. Meanwhile, existing household practices [52,53] and heating systems [4], expectations of comfort [54], and access to wider heating infrastructures, such as gas distribution networks [55] and moving house [10] also influence S-RET adoption decisions.

A key implication from these studies on the adoption of S-RET is the high emphasis on the particularities of detached houses, adopter needs and resources, means and knowledge they have at their disposal for making S-RET adoption decisions. The same S-RET solutions can compete or complement each other depending on the local and national context as well as on the particularities of house and adopters [6].

2.3. Multiple heating systems use in detached houses

Existing literature on multiple heating systems in households is relatively sparser than research on S-RET adoption. Observing the wood heating practices of Finnish detached house dwellers, Rinkinen [56], nonetheless, posits that households tend to embrace diversity in their heating solutions as well as a sense of sovereignty. Studies on hybrid heating arrangements suggest that house owners generally view hybrid heating arrangements positively due to their relatively lower acquisition and operation cost and the possibility to add them one by one, retaining old systems in place, and due to the ensuing capacity to better respond to climatic or price variations (see below) [2,47]. However, their higher installation costs might be a barrier for the adoption, as is the case with any new heating arrangements [57].

In line with studies presented in Section 2.2, Michelsen & Madlener [58] note that adoption motivations for hybrid heating arrangements are guided by existing heating technologies as well as those to be incorporated to existing heating arrangements. Räihä & Ruokamo [2] in turn observe district heating or ground source heat pump (GSHP) households are less likely to consider the adoption of supplementary heating technologies than households using direct electric heating, pointing to the influence of existing heating systems in S-RET adoption as well as the preventive effect of expensive prior investment (also [4]). Moreover, they note that the adoption of an S-RET is likely to lead to a domino effect of further adoptions (see also [13]). Others, too, have noted the importance of local infrastructural factors such as the size and condition of the house [53,59] on S-RET adoption.

In their UK case study [4], observe that instead of replacing existing heating systems, low-carbon solutions are typically integrated into them to retain the value provided by conventional technologies. Similarly, up to 20 % of Finnish oil-heaters retain their old system in reserve instead of scrapping them [60]. Juntunen [13] and Hyysalo [23] posit that the intermittent nature of S-RET and the demands of the Nordic climatic conditions tend to drive heating systems towards hybridization in household. Only few S-RETs, namely GSHP and AWSHP, and also ASHP and micro-wind, can provide year-round low effort heating but require considerable investments. Other household scale S-RETs are relatively more inexpensive and provide improvements to existing heating systems and complementarities to each other: for instances cold but sunny springs and long summer days are well suited for solar technologies, dark but relatively mild autumns and warm spells mid-winter suit air-source heat pumps well, and the physical arduousness of solid wood heating is found bearable for relatively short high heat demand peaks at mid-winter. Hyysalo's [23] analysis of heat-pump diffusion in Finland conjectures that due to the high uptake of ASHPs the character of Finnish energy renovations has shifted from system replacement towards the integration or parallel operation of S-RET alongside existing systems.

3. Methodology

3.1. Research context: heating in Finnish detached houses

In 2021, the heating of buildings comprised 27 % of total energy used in Finland. Finnish buildings are well insulated but, as is typical of Nordic countries, people are accustomed to high and stable indoor temperatures, the average being 21 °C [61,62]. Almost half (47 %) of the Finnish population lives in detached houses [21], and home-ownership rate in Finland is 71 %, which is higher than in most Western European countries [63], and thus large portion of consumers can directly make investments decisions about their heating arrangements.

Residential space heating in Finland has historically featured a varying mix of oil, wood, coal, gas, peat and direct electric heating and the more recent rise of heat-pump produced heating, 'ambient heating'. Until the 1980s residential space heating was solely fossil and wood energy based [62]. In the 1990s and 2000s, district heating and direct electric heating advanced, while coal, peat and natural gas remained marginal as heat sources. Distributed and renewable energy diffusion advanced during the 2000s [23]. At present, solid wood is the most extensively used energy carrier for heating in detached housing, covering 39 % of heating energy usage [64]. With the prehistory of a 1978 statute requiring houses to have an alternative heating form, currently 86 % of houses and cottages are equipped with a fireplace [65], and almost all newly build detached houses are fitted with one [66]. By 2022 an estimated 774,000 Finnish detached houses (73 %) were equipped with one or more heat pumps used for heating[2]. Also, solar PV capacity has increased notably [69] along with smaller shares for wood pellets and solar heat. While it has been noted that wood heating enjoys a special cultural-historical status in Finland, it has also been observed that wood heating technologies often provide a backup or a backbone for heating arrangements to which other heating technologies can be integrated [10,22].

This progression of user-end energy transition in Finland has not yet comprehensively affected how official statistics about energy use in buildings are collected. There are three statistics on household heating (see Fig. 1, parts a–c), the so-called *Buildings and free-time residences (116h)* [70], *Households' Consumption (13qk)* [20], and *Energy consumption in households (11zr)* [64] databases. The first is based on the Building and Dwelling Register maintained by the Digital and Population Data Services Agency, where buildings are classified based on their primary heating system during construction. That information is only updated if a building undergoes renovation requiring a permit, which most energy renovations do not [71]. This renders the database largely outdated. The second database is a subsection of household consumption survey renewed every five years, which surveys consumers only for their primary heating system.

The third statistic [64] describes the amounts of heating fuels used in detached and semi-detached houses. Here energy consumptions are calculated from sales figures of different fuels to different energy technologies, complemented by modelling of consumption patterns and equipment use in typical households. Inaccuracies of this method particularly in fully capturing S-RET diffusion and energy use, are reported by the corresponding authority [72].

Focus on all these three statistics is on "primary" heating which has enabled comparability and reproducibility of information across time and space which is important in statistics [73]. Yet, hybrid heating arrangements in their diversity, as we demonstrate below, are residual [74] or left-out phenomena [73,75] that challenge existing classification schemes. Statistics built around "primary heating" may have given an adequate picture of the heating of homes before, but the rapidly progressing energy transition in the detached house sector has left many phenomena outside of the official statistics.

In the Finnish case, the three statistics produce images of direct electric heating as the dominant heating source in detached and semi-detached houses. Importantly, regarding the research in this paper, the additive sum of different renewables in Finnish detached houses (see above) and the smallest amounts of non-renewable heating systems implied by any of these statistics amounts to over twice as many heating systems as there are detached houses – indicating that the statistics likely overlook the existence of hybrid heating system arrangements.

The extent and ways by which renewables are adopted in detached

[2] 1,453,621 heat pumps have been sold in Finland by 2022. 774,000 estimate based on the industry estimate of the distribution of less than 26 kW systems into detached houses, commercial buildings and summer houses and an estimated 15-year replacement cycle for air source heat pumps (ASHP) and an industry estimate of to date 10 % of the houses featuring more than one heat pump [67,68].

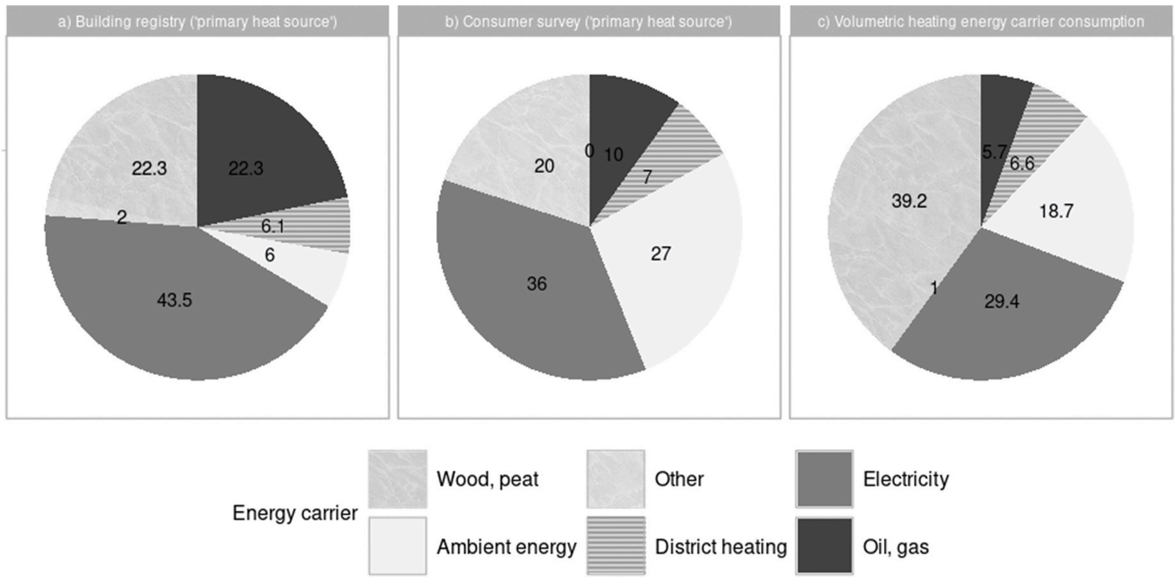

Fig. 1. a–c. Primary heating sources of small houses (% of all houses), based on (a) building registry (left), in 2021 [70] and (b) consumer surveys (middle), in 2022 [20].[3] (c) Chart on the right depicts shares (%) of volumetric (GWh or GJ) energy sources consumption for heating in small houses in 2021 based on sales figures and modelling [64]. 'Ambient energy' denotes heat pumps as 'primary' heating sources (GSHP in (a); GSHP and ASHP in (b)) or energy produced by heat pumps (in c). Category 'Other' with 20 % popularity in (b) typically denotes wood heating because because wood was not an option in the survey.

[3] Based on preliminary survey data for 2022 (collected from 1 January 2022 to 30 June 2022), covers only detached (not semi-detached) houses.

housing are likely affected also by some further country specific conditions. Regarding heat–pump based electricity, electricity prices in Finland have continuously been among the lowest in Western Europe (EU-15) [76]. Finland was a pioneer in smart meter roll-out, completing it in the first years of the 2010. The Finnish population is also at the top of the UN education index and the country has retained some do-it-yourself culture, particularly in the sparsely populated countryside, which both contribute to having the skills to adopt and adapt new equipment, as well as to the capacity to search for and appropriate information [30,77]. Yet, over the years, the adoption of S-RETs has only been modestly advanced by subsidies that have addressed energy efficiency and renewable energy use in the residential sector in Finland, such as subsidies for replacing oil-based heating systems at the end of the 2000s and again in 2020.

3.2. Data and methods

Our analysis is based on data from a *Survey on energy prices and Finnish homes* conducted on an online platform in the early autumn of 2022 among the members of *Suomen Omakotiliitto ry* (Finnish Home Owners' Association; www.omakotiliitto.fi; that has 70,000 citizen members across the country). The survey design was led by an Aalto University researcher (the main author of this paper) who involved experts in three universities and in an energy consultancy company VaasaETT LTD and the homeowner association management to contribute or give feedback in research design, survey question formulation, and the user-friendliness of the survey. Aalto University's Research Ethics Committee conducted an ethical assessment of the survey in June 2022 before the public launch of the survey. The survey was online in August and September 2022 and it was actively promoted to the members of the association and through the communication channels of the research project ORSI (www.ecowelfare.fi). Survey questions can be found in Supplementary material in the original language (Finnish) and as translated into English.

The primary motivation of the survey was to map the experiences of Finns on the cost of energy under the energy crisis. In parallel, relevant background information such as heating systems in use, fuel expenses, and some socio-demographic details were queried. Respondents were requested to fill the survey only for one apartment used all year round. This paper reports the analysis on part of the survey data considering the versatility of respondents' heating systems that were mapped through a diverse set of questions.

- Which of the following energy sources are used in your apartment? (+Others, what)
- Which of the following energy-producing or consuming appliances do you use? (+Others, what)
- Do you know the total energy costs of your household in 2021?
- What were your household energy costs in 2021? € (estimate) or € (exact figure).
- How much did you pay for each energy source last year in 2021? (respondent was asked to detail costs per fuel on dedicated rows; there was also a row 'Others, what'.)
- Did you get some free fuel, such as wood?
- Which of the following heating or energy renovations have you made in your apartment in the last two years? (+Others, what)

Data analysis tool R was used for analysing survey data. There were 5220 responses to the survey in total. We deleted 444 duplicate or incomplete responses as well as some that were labelled unreliable (see below) based on the initial data analysis. Survey data pre-processing is explained in detail in Ref. [78]. Additionally, we excluded respondents living in apartment buildings and terraced houses. The final number of responses analysed in this article is 4276.

We identified user numbers for different heating fuels (oil, wood, pellets, gas), heating solutions (electric heating, district heating), heat pumps (ASHP, GSHP, AWSHP, and exhaust-air heat pump (EAHP)) and for solar panels and solar thermal collectors. During the data analysis, it was noticed that respondents with various heating profiles mentioned that they use 'electric radiators'. An electric radiator was interpreted as electric heating in all cases where there was no risk of misunderstanding. Even with that risk, electric heating would only be used in part of the apartment or only as a backup heating radiator. The choice is consistent with the purpose of our research, which is to map the variety of installed heating devices. On the other hand, 'electricity' (without the 'electric radiators' box ticked) as a form of energy used by a respondent was not enough to categorize them as using electric heating. In these cases, and in the case of uncertain heating profiles, we conducted a more detailed analysis.

We assumed that the respondents keep their homes warm year-round. As such, they must utilize at least one of the following: electric heating, oil heating, district heating, gas heating, ASHP, GSHP, AWSHP, a pellet burner or some kind of wood heating technology. We assumed that solar panels, solar thermal, and an EAHP alone could not cover the year-round heating needs on Finland's latitudes. The key indicator of the reliability of an answer line was the reported energy cost. If the respondent had left their energy costs unreported or the magnitude of their energy costs was unrealistic, an iterative reliability assessment was undertaken, and their heating profile was compared to other similar ones. For example, if a respondent had not been identified as an electric heater, but could not be identified as heating with oil, district heating, GSHP, AWSHP, pellets or wood, but their reported electricity bill for 2021 exceeded 8 €/m^2, they were marked as heating with electricity, because their energy costs corresponded to the order of magnitude that other respondents using electric heating had paid. Descriptive statistics of sample can be viewed in Table A1 in Appendix A. Depending on their county (province) of residence, each respondent was categorized into one of four 'weather regions', that are defined in an official building code [79], formed according to differing heating needs across the country (position of counties in weather regions in Table A1). Our hypothesis was, that elevated heating needs in the more northern regions would also motivate installation of additional heating systems.

Because the sample was not randomized, and the survey was marketed particularly to the members of the Finnish Home Owners' Association, the sample cannot be considered statistically representative of the Finnish detached housing stock. However, the demographics of our sample are surprisingly close to the overall Finnish situation for many key figures, such as household size and median income (Table 1), while the respondents are slightly more aged and more educated than the overall population. The sample is biased towards detached houses with higher than average floor area, and to houses built in the 1980s (Fig. 2). In terms of geographic distribution, Southern and South-Western regions are clearly overrepresented, but the remaining distribution is roughly even compared to Finland statistics (Fig. 2).

Table 1
Descriptive statistics of the respondents compared with Finnish population in detached and/or semi-detached housing in 2021. Mean values (Median values in brackets).

Variable	Sample (N = 4276)	Finnish population	Source
Age (years)[a]	59 (62)[b]	53 (54)[b]	[80]
Education level	Basic or no education 5 %; Higher-level tertiary or doctorate 28 %	Basic or no education 20 %; Higher-level tertiary or doctorate 12 %	[81]
Gender	Male 63 %	NA	
Annual disposable income of household (€)	48242 (52800)[b]	56491 (49016)[b]	[82]
Household size (N inhabitants)	2.44 (2)	2.36 (2)	[83]
Floor area (m^2)	154 (141)	144 (NA)	[70]
Building year	1979 (1983)	NA (NA)[c]	
Number of different energy technologies or fuels used	2.503 (3); SD = 0.85	NA	

[a] For people over 18 years.
[b] Values counted from midpoints in intervals for age and income optionable in survey (i.e., 62 in 60–64 years).
[c] See Fig. 2.

Connectedness of increasing number of energy technologies (variable 'N_systems') with respondents' socio-demographic background and building variables were explored with basic statistical tests of association. N_systems was treated as a numeric variable (Point-biserial correlation coefficients) but also as a categorical (CramerV and Kendall's tau-b or tau-c coefficients). Treating N_systems also in categories is motivated due to the low variance: most respondents (79 %) had two or three systems (Table A1 in Appendix A shows distribution) but also because the everyday life situation where the house has just one, single, heating system is distinctively different from the situation where the family can effectively use 4–6 different, alternating systems. Anova tests were performed with independent variables that was count data (building floor area and the age of building) and with ordinal variables.

To determine the impacts of multiple variables' simultaneous presence, two logistic regression models were built. The binary dependent variables were whether or not the household had one energy technology (N_systems = 1; Model 1) or over three systems (N_systems = 4–6; Model 2). All available independent variables were fed into models, however heating variables were restricted to major heating technologies or fuels used (oil, AWSHP, district heating, electric heating and GSHP) because including all energy technology variables produced severe multicollinearity. Reference values for category variables were 18–29 years of age; 42000–63600 € of annual household disposable income; 'employed' employment status; basic level of education and 'South-Western' for geographic region. All prerequisites for logistic regression [85] such as no overdispersion were assessed to be met. Models were trained with 70 % of sample leading to similar accuracy levels with testing datasets (11.4 % and 11.4 % for Model 1 and 9.9 % and 10.3 % for Model 2). Models converged after 6 Fisher scoring iterations.

4. Results

We identified 162 different kinds of hybrid energy arrangements in our data (see Table A2 in Appendix A for the full list). By hybrid energy arrangements we refer to the totality of different energy technologies or fuels used in a household, which can be composed of one or more different technologies.[4] As Table 2 demonstrates, 38 % of the respondents utilize three, 38 % two, and 10 % four or more energy technologies in their homes and only 11 % rely on a single energy source. Wood, ASHP and electric heating are the most widely-utilized single fuels or technologies. Popularities of each technology can be found in Table A3 in Appendix A. Table 3 demonstrates the popularities of the arrangements of energy technologies (Full collection in Table A2). The most popular arrangement included direct electric heating, wood heating and an ASHP, used by 23 % of the households. After this combination, heating arrangements fragment quickly. The second most popular combination (wood with electric heating) is utilized by just 9 % of the respondents (see Fig. 3).

4.1. Different energy technologies and hybridity

As indicated before, different heating systems appear to have different propensity to affect the extent of hybridization of heating arrangements. Variation is demonstrated in Fig. 4 where users of each 'major' heating technology or fuel are represented, when being parts of differing heating systems arrangement sizes (N_systems). As per their correlation coefficients (Table 4), ASHP (0.62), wood (0.51), solar PV (0.47) and electric heating (0.32) are the most 'hybridized' energy

[4] We chose to talk about 'hybrid energy arrangements' as some of our respondents (0.8 %) combine a heat source with solar PV. While, solar PV cannot be considered a heating source on Finnish latitudes, it contributes to a household's energy portfolio and can contribute towards the efficiency of heat pumps for instance, as demonstrated in by literature [86].

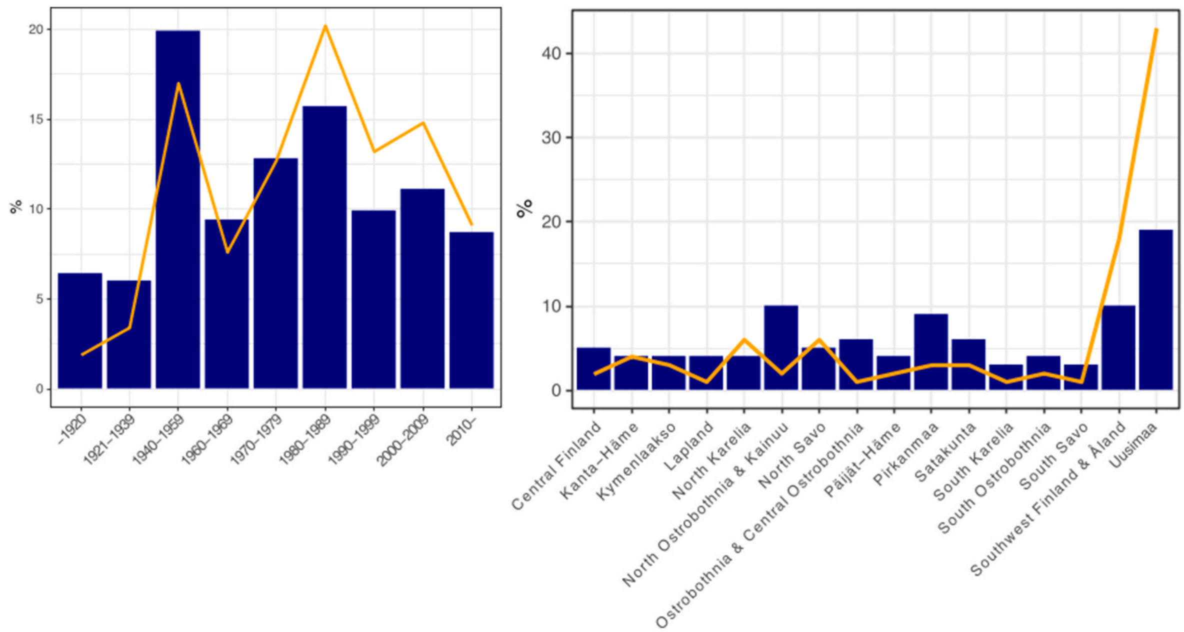

Fig. 2. Regional coverage and the age of buildings in sample (red lines) compared with overall population (blue bars) [84] of detached and semi-detached houses in Finland. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Number of energy technologies among fuel and energy technology users.

	All sample		GSHP owners (662)		District heating (275)		Oil users (555)		AWSHP owners (382)		Electric heating owners (2088)		Wood users (3324)		ASHP owners (2520)	
N_systems	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
1	486	11	119	18	75	27	75	14	33	9	78	4	99	3	3	0
2	1620	38	313	47	128	47	211	38	133	35	620	30	1142	34	587	23
3	1745	41	188	28	62	23	191	34	149	39	1111	53	1665	50	1526	61
4–6	425	11	42	6	10	4	78	14	67	18	279	13	418	13	404	16
Total	4276	100	662	100	275	100	555	100	382	100	2088	100	3324	100	2520	100

Table 3
Most popular energy technology arrangements in sample (N = 4276) and popularities of all single-source arrangements (Full table in Table A2 in Appendix A).

Popularity[a])	Arrangement	N	%
1.	Electric heating, wood heating and ASHP	982	23
2.	Electric heating and wood heating	401	9.4
3.	GSHP and wood heating	230	5.4
4.	Electric heating and ASHP	196	4.6
5.	Wood heating and ASHP	183	4.3
6	Electric heating, wood heating, ASHP and PV	152	3.6
7.	Only GSHP	118	2.8
8.	Oil heating, wood heating and ASHP	115	2.7
9.	GSHP, wood heating and ASHP	114	2.7
10.	Oil heating and wood	110	2.6
11.	Only wood heating	99	2.3
14.	Only electric heating	78	1.8
15.	Only district heating	74	1.7
16.	Only oil heating	73	1.7
27.	Only AWSHP	33	0.8
44.[a])	Only pellets	4	0.1
45.	Only ASHP	3	0.1

[a]) Shared 44. place, for example, was given for 8 unique arrangements that only had 4 users each.

technologies or fuels. On the other hand, GSHP and district heating have negative coefficients indicating a higher probability to appear in a single-heating-system arrangement, however the effect is quite weak. Indeed, 18 % of GSHP owners have just their single system (GSHP) while only 3 % of wood-users rely on wood-only (Table 2). Räihä and Ruokamo [2] arrived at similar results. District heating households had only 2.03 energy technologies or fuels in use and GSHP owners 2.23, on average, while the whole sample average was 2.50. Solar collector owners had on average 3.67 energy technologies and PV panel owners 3.65. Mean and SD values of N_systems connected with all single energy technologies can be found in Table A1 in Appendix A. On the other hand, oil heating and AWSHP ownership are not statistically significantly connected with the number of used systems (coefficients are nearly zero).

4.2. Socio-demographic and building characteristics and hybridity

Only weak direct correlations between many socio-demographic features and an increasing number of energy technologies were found, as Table 4 indicates. CramerV coefficient was less than 0.1 for all tested variables. Moderate correlation would in principle require at least 0.1–0.29 [87]. Household income (Table 4) seems completely unconnected due to the high p values which does not enable the rejection of the null hypothesis. However, the differences between income-groups were non-linear. Tukey comparison of means tests (Table 5) revealed a statistically significant difference between two middle-income groups. The third-lowest income group had 0.25 systems more, on average, than a single higher-earning group (the sixth; find income groups details in Table A1 in Appendix A). Education level neither demonstrated being associated with the number of energy technologies at home. There was a small (0.1 systems) difference between two education groups (Table 5).

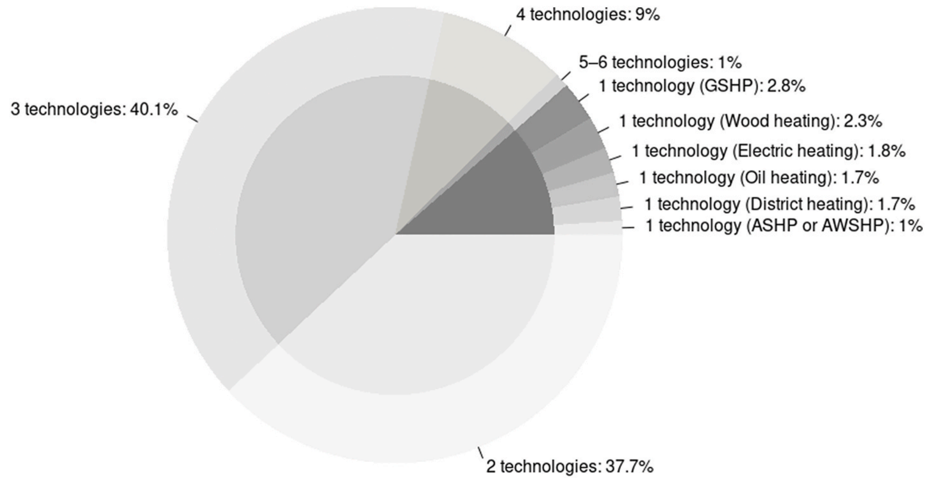

Fig. 3. Shares of respondents using different numbers of energy systems. Single-energy-source cases also visible. Source: Authors.

When tested between 'higher' and 'lower' education groups, differences disappear completely (Table 4). Employment status was connected in a statistically significant manner: unemployed had 0.43 fewer energy technologies than entrepreneurs, and 0.3 fewer than the employed. Statistically significant difference could also be found between households in two unique geographic regions. Respondents in the most northern region ('North') had 0.3 systems fewer than people in the most southern region ('South-West'). The difference can be probably explained by modest diffusion of solar energy technologies in more northern latitudes where solar irradiation intensity is lower.

Gender was also weakly associated with hybridization: female respondents had a smaller number of energy technologies installed. Age of respondents (Table 5) and building age (Table 6) were non-connected with hybridization. However, higher floor areas of buildings were connected with a higher number of energy technologies in use. Nevertheless, differences are tangible only when comparing houses of 3 systems (mean floor area 151 m^2) with houses of 4 systems (mean floor area 163 m^2), as per Tukey multiple comparison of means test (Table 6). Fig. 5 visually demonstrates a conclusion that existing energy technologies, such as electric heating (part a) or a GSHP (part b) are clearly more significant determinants of hybridization than floor area (part c) and gender (part d) while differences across employment situation (part e) and education levels (part f) are clearly less tangible.

Logistic regression modelling allows studying simultaneous impacts of background variables on a binary output. In the following sections we study the possible connection of respondents' background with the two uttermost cases: having just one energy technology or fuel in use (Section 4.2.1) and using four or more energy technologies (Section 4.2.2).

4.2.1. Households using only one energy technology or fuel

Logistic regression modelling (Table 7, Model 1) revealed that certain existing major heating installations, namely electric heating, AWSHP or oil heating significantly reduced likelihood of one-system heating. In addition, respondents who were unemployed had almost 2 times higher odds of having just one energy technology, compared with the reference group, employed. Families with children (number of family members three or more) had 1.5 higher odds of having just one energy technology or fuel in use than the reference group, two-person families. Women had 1.3 higher odds compared with men. Floor area was also statistically significantly correlated meaning that increasing floor area reduced the likelihood of having just one energy technology. However, the actual differences in floor areas between one-system homes and the rest are actually not large (Table A1). Younger age of building reduced the likelihood for having only one energy technology

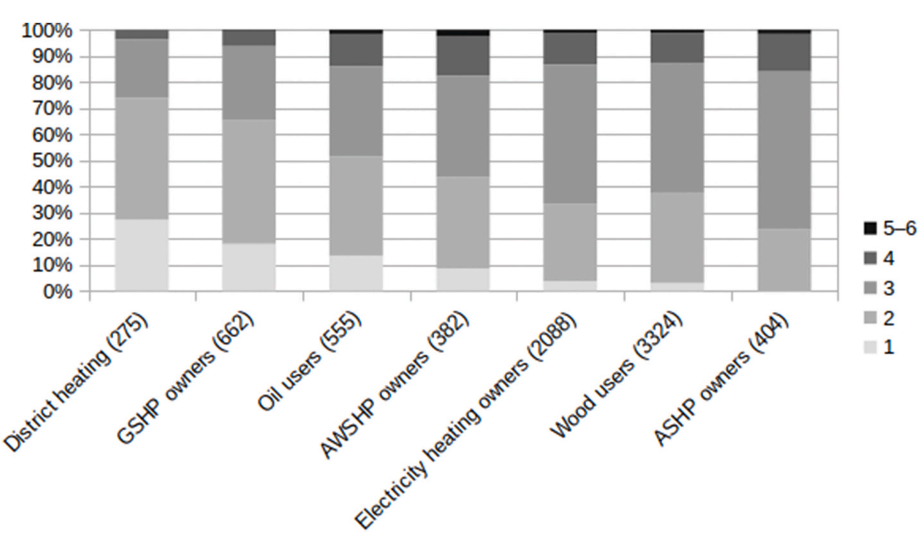

Fig. 4. Number of utilized different heating systems (N_systems) per heating system owners/fuel users. Each bar represents all users of specific heating type, and within, the shares (%) per N_systems in use. In brackets their total number in sample. Bars put in the left-right order depending on their Point-biserial coefficients in Table 4.

Table 4
Tests of association between various independent variables and the number of energy technologies or fuels in use (N = 1,2,3,4,5–6).

Dichotomous variables				
Independent Variable	Chi2 test p-value	CramerV	Kendall's tau-c	Point-biserial
GSHP owners (no vs yes)	<2e-16	0.1442	−0.1096	−0.1360
District heating users	<2e-16	0.1585	−0.0782	−0.1481
Oil users	0.0004	0.0690	−0.0038	0.0016
AWSHP owners	1.41e-06	0.0874	0.0352	0.0659
Electric heating users	<2e-16	0.3363	0.3507	0.3156
Wood users	<2e-16	0.5707	0.4617	0.5132
ASHP owners	<2e-16	0.6566	0.6829	0.6209
Solar photovoltaic owners	<2e-16	0.5996	0.3053	0.4679
Solar thermal owners	<2e-16	0.2632	0.0398	0.1744
EAHP owners	<2e-16	0.2193	−0.0017	0.1926
Gas heating users	0.807	0.0194	−0.0017	−0.0150
Pellet users	<2e-16	0.2413	0.0278	0.1299
Gender (men vs women)	5.98e-08	0.0959	−0.0869	−0.0879
Education (lower vs high)	0.0812	0.0441	−0.0083	−0.0064
Category variables				
Variable	Chi2 test p-value	CramerV	Kendall's tau-b or tau-c	Pearson corr
education (in 5 categ.)	0.0207	0.0434	0.0196	
income	0.5360	NA	NA	
age (in 10 categories)	0.0002	0.0687	(non-linear)	
family size	0.0013	0.0537	0.0310	0.0262
weather region	0.0088	0.0414	−0.0282	
employment (in 5 categ.)	<0.0001	0.0571	−0.0093	

but because differences are counted on years, not on decades, they are unmentionable (see Table 6 and A.1). Respondent's age or education, household income level or the geographic region were not statistically significantly connected.

4.2.2. Households having 4–6 different energy technologies

Having electric heating, AWSHP, oil heating or an GSHP increased the likelihood of having 4 or more different energy technologies in use. In addition, odds of having 4–6 systems were almost 3 times higher among post-graduates than people with basic education, and 1.8 higher for entrepreneurs than the reference group, employed. Curiously, respondents in category 'out of work' (for reasons not queried in the survey but also temporarily such as being on parental leave) increased the odds of living in a hybrid heated home. Women had smaller odds of having 4–6 systems than men. Indeed, only 6.6 % of female respondents used 4–6 systems compared to 11.9 % of male respondents (Table A1). Increasing floor area was connected, but a mentionable difference could only be found only between houses of 4 systems and houses with 3 systems (Table 6 and A.1): the former had 9.4 square meters higher floor area than the latter. Respondent's age, income level, geographic region and the age of building were not statistically significantly connected.

To conclude, these logistic regression tests revealed some further information about the connectedness of certain socio-economic background features with the two uttermost situations in hybridization (N_systems = 1 and N_systems = 4–6). Due to differing treating of variables in univariate and multivariate tests, the correlation tests (Sections 4.1 and 4.2) where hybridization was treated as a steadily increasing numeric variable are not completely comparable with the LR test results (Sections 4.2.1 and 4.2.2), but findings are complementary.

5. Discussion

5.1. Hybridization among variously heated homes

The diversity and fragmentation of detached house heating into more than 160 hybrid arrangements underscore the importance of local, household level conditions and rationales in shaping heating arrangements [6,59]. People are creative and able to devise and design energy systems suitable to their particular needs and resources [4,23,46]. Most hybrid heating arrangements (73 %) in our data are quite unique, opted for by less than 10 households, which corroborates these earlier observations.

There are several logical reasons why different fuels or energy

Table 5
One-way ANOVA for ordinal variables with N_systems (numeric) and when significant, results of Tukey multiple comparison of means test. Mean and SD values of N_systems per each respondent group in Table A1 in Appendix A.

	Anova			Tukey test (sig)		
Variable	df	F	p	compared groups	diff	p
education	4	4.274	0.00188**	Upper secondary vs Lower tertiary	−0.10	0.01739
income	9	8.423	0.00372**	14400–20400 € vs 42000–63600 €	−0.25	0.00771
age	11	2.709	0.00175**	N/A	N/A	>0.053
age (10 groups)	9	2.564	0.00612**	55–59 years vs 45–49 years	−0.19	0.04824
weather region	3	6.462	0.000232***	North vs South-west	−0.30	0.00034
family size	5	5.644	3.42e-05***	1 member vs 2 members	−0.19	0.00001
				1 member vs 4 members	−0.15	0.03532
				1 member vs 5 members	−0.22	0.02267
employment	4	5.077	0.00044***	Unemployed vs Entrepreneur	−0.43	0.00018
				Unemployed vs Employed	−0.30	0.00253
				Unemployed vs Retired	−0.33	0.00078

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1.

Table 6
One-way Anova for numeric building variables with N_systems (category) and Tukey multiple comparison of means test when significant. Mean and SD values of N_systems per each respondent group in Table A1 in Appendix A. In the last column, Pearson correlation coefficients.

	Anova			Tukey test (sig)			Corr
Variable	df	F	p	compared groups	diff	p	
floorarea	4	3.45	0.00802 **	4 systems vs 3 systems	9.43 m^2	0.0368	0.0156
buildingyear	4	0.758	0.552	N/A	N/A	>0.48	0.0158

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1.

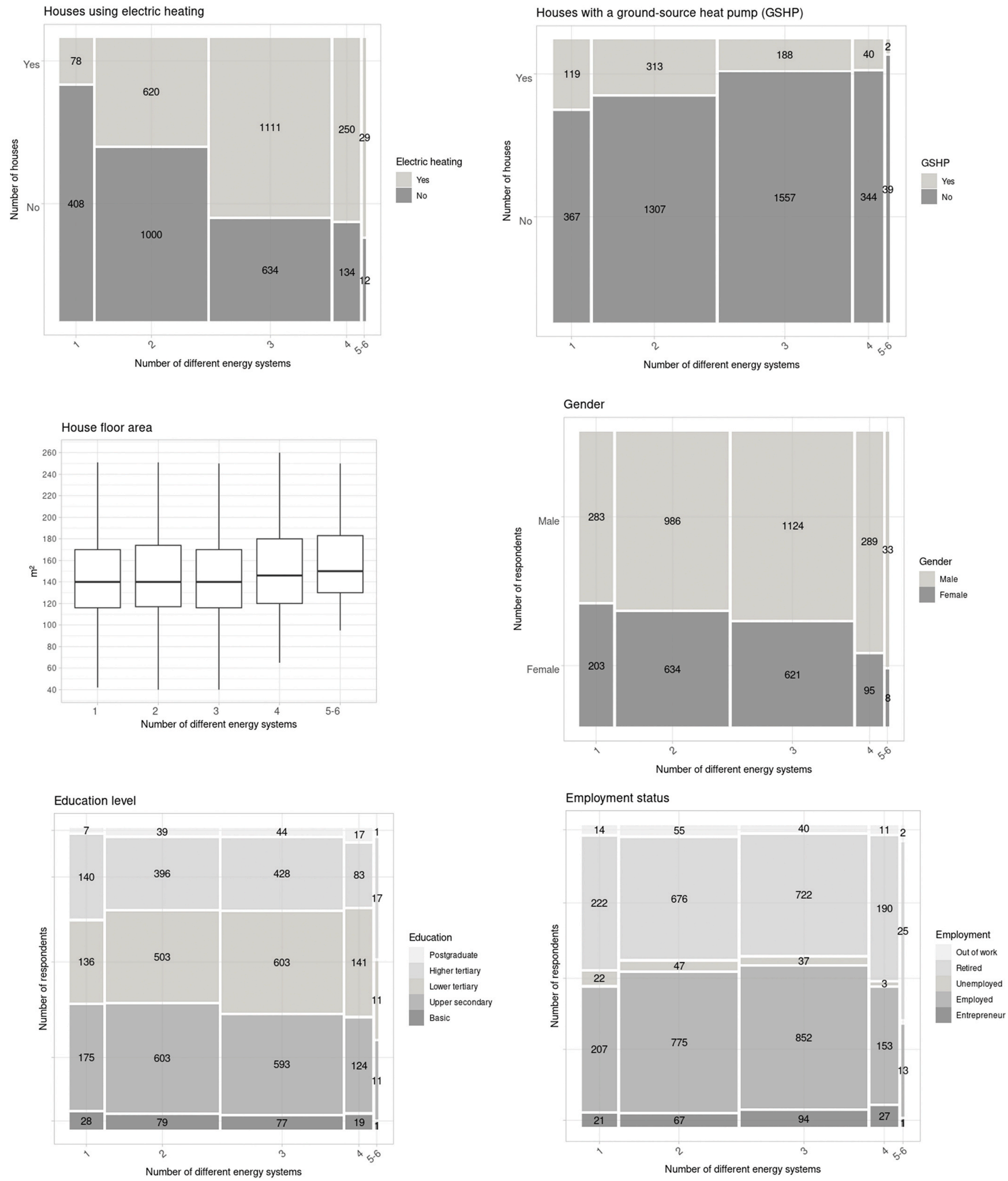

Fig. 5. a–f. Number of energy technologies in homes with a) electric heating; b) a ground-source heat pump and c) their floor areas. Hybridity and respondent's d) gender; e) employment status and f) education level. Numeric labels on segments on Figures a–b and d–f indicate the respondent number per each segment.

solutions, such as wood, ASHP and electric heating appeared mainly in hybrid combinations. The prevalence of wood, in particular, is not surprising, considering the important cultural-historical status of wood in Finnish heating [10], encouraged by building regulation [88] and building tradition [65,66]. Neither is the popularity of the ASHP in hybrid arrangements surprising, considering their recent, rapid and wide surge in sales [67,89], and the relatively low investment costs (400–3000 € compared to other S-RETs e.g. median costs of a GSHP is

Table 7
Logistic regression models predicting situations where the number of different energy technologies is one (Model 1) and the number is 4–6 (Model 2). Numbers in bold indicate statistically significant correlations with p-values of: '.' <0.1, '*' <0.05, '**' <0.01, '***' <0.001.

	Model 1: N systems = 1				Model 2: N systems = 4–6			
Variable	β	exp (β)	p value		β	exp (β)	p value	
Intercept	18.6552	1.26E+08	0.0001	***	−14.9369	3.26E-07	0.0107	*
Age 35-49	0.0327	1.0333	0.9268		0.3550	1.4262	0.4072	
Age 50-59	0.0440	1.0450	0.9016		0.3255	1.3847	0.4469	
Age 60-69	0.1919	1.2115	0.6159		0.3662	1.4423	0.4232	
Age 70-	0.4286	1.5350	0.3054		0.4369	1.5479	0.3685	
Income <15600	0.1396	1.1498	0.6592		−0.4402	0.6439	0.2504	
Income 15600-27600	0.3411	1.4064	0.1096		−0.2621	0.7694	0.2839	
Income 27600-42000	0.0889	1.0929	0.5908		−0.1660	0.8471	0.3232	
Income 63600-104400	−0.1640	0.8487	0.4084		−0.3400	0.7117	0.0776	.
Income >104400	0.0812	1.0846	0.8345		−0.4005	0.6700	0.3230	
Education Upper secondary	0.1433	1.1540	0.6204		0.1508	1.1627	0.6517	
Education Lower tertiary	−0.0669	0.9353	0.8226		0.2062	1.2289	0.5437	
Education Higher tertiary	0.2267	1.2544	0.4609		0.1316	1.1406	0.7095	
Education Postgraduate	−0.7580	0.4686	0.2037		1.0954	**2.9904**	0.0131	*
Entrepreneur	−0.1984	0.8201	0.5234		0.6206	**1.8600**	0.0273	*
Unemployed	0.6625	**1.9397**	0.0466	*	−1.5873	0.2045	0.1193	
Retired	0.1358	1.1455	0.5527		0.3041	1.3555	0.2149	
Out of work	−0.1448	0.8652	0.6986		0.8534	**2.3476**	0.0205	*
Region: Central Finland	−0.2956	0.7441	0.0659	.	−0.0030	0.9970	0.9853	
Region: Northern Central	−0.2273	0.7967	0.2368		−0.2450	0.7827	0.2409	
Region: North	0.0759	1.0789	0.7980		−0.8053	0.4469	0.1258	
Gender: Female	0.2883	**1.3341**	0.0294	*	−0.4572	**0.6331**	0.0035	**
Family size: 1	0.1686	1.1836	0.3781		−0.1655	0.8475	0.4704	
Family size: 3–6	0.4154	**1.5149**	0.0201	*	−0.0509	0.9504	0.7785	
Floor area	−0.0024	**0.9976**	0.0406	*	0.0037	**1.0037**	0.0005	***
Year built of house	−0.0100	**0.9900**	0.0000	***	0.0050	1.0051	0.0845	.
District heating	0.0236	1.0239	0.9120		0.6779	1.9697	0.1419	
Electric heating	−2.3758	**0.0929**	0.0000	***	2.1219	**8.3473**	0.0000	***
Oil heating	−0.8517	**0.4267**	0.0000	***	1.5109	**4.5307**	0.0000	***
AWSHP heating	−1.1283	**0.3236**	0.0000	***	1.6768	**5.3484**	0.0000	***
GSHP heating	−0.3229	0.7240	0.0771	.	1.1459	**3.1451**	0.0002	***
McFadden R^2	0.136				0.104			
AUC value	0.723				0.699			

21,000 €) that makes additive installation of ASHP financially viable for many households. Based on our data we cannot ascertain whether ASHPs are used for heating or cooling. Product development have rendered new ASHPs efficient, capable of covering year-round heating needs in Finnish latitudes [23,90], making it a viable choice for electricity or oil heated homes to decrease energy bills, and for wood-heated homes to alleviate the physical burden required to ensure consistent indoor temperatures [22]. Considering that the survey was conducted in Finland where the heating degree days (HDD) index is the highest in Europe [91], we can assume that households having installed an ASHP are using it at least for heating even if they might also use their ASHP for cooling in the summer.

Also, the more expensive S-RET systems, that is the AWSHPs and GSHPs, are combined with more traditional arrangements. AWSHP is often described as a replacement for oil heating [92], in a process that is subsidized [93]. Still, 81 (15 %) of 555 homes in our sample with oil heating, have both an AWSHP along with an oil boiler, forsaking the replacement subsidy. Where oil is combined with an AWSHP, we can assume seasonal patterns for the utilization of different heating energy technologies, where oil enters the picture during the coldest periods of the year when the performance levels of the AWSHP drop. There are also 10 houses with both GSHP and oil heating. Further scrutiny into these homes pointed out higher floor areas (mean 164 m^2) and higher total number of technologies (mean 3) and family sizes (mean 3 members). As our statistical test also found a general, statistically significant, connection with higher floor areas with hybridization, we could conclude that the accumulation of energy systems in some cases might mean situations where different floors or sections of larger buildings are heated with separate heating techniques which is a pragmatic choice for those families to gain savings to their heating costs.

Nonetheless, GSHP appears most probably as the 'lonely' single energy technology in buildings (18 % of GSHP owners in our dataset have just this one energy system). This could be explained through the fact that GSHP is the most popular heating system for new build detached houses [68] and GSHP is a significant investment (as is building a new home). In their case it can be assumed that the hybridization development will be topical only in the future. An existence of a district heating system is another heating technology that more probably appears alone (74/275 = 27 % of district heating owners). One reason for this might be that utilities' heat flow charge has a typically 50 % fixed price component, which renders energy provision by other energy carriers relatively disadvantaged.

Nevertheless, also the majority of district heating installation owners have additive or complementary energy technologies, similarly to other respondents in the sample. The 16 unique combinations produced by district heaters (typically with wood, PV and ASHP, but also with a solar heat collectors and EAHP) suggest that the inclusion of S-RETs does not necessarily streamline, but rather just adds diversity [4] to heating arrangements, and moreover that households can bring different energy technologies together in unexpected configurations [4,13].

5.2. Hybridization and the socio-demographic background of households

Only weak differences are found regarding socio-demographic background of respondents when 'hybridity', as an increasing number of energy systems, was studied. This is actually not very surprising because the *number* of energy systems (three, typically) comes with a broad range of combinations and energy system qualities and use practices. Many authors (e.g. Ref. [58]) emphasize that any association found between hybrid system adoption and socio-demographic factors are bound to context-specific factors such as householders' earlier experiences with S-RET, their housing type, available grants, and also the time of study. Most importantly, the already existing household energy infrastructure prominently determines S-RET adoption and hybridization [6,58]. This is aligned with our findings.

When we separately studied the background of households with just one energy system, we found that unemployed respondents, women, and families with children (number of family members three or higher) typically belonged to this group. As families with children are also more often experiencing an emotional burden from their energy costs (subjective energy poverty) [78], it would be important to understand how different technology arrangements spread or can spread across socio-demographic groups and whether the energy transition should be advanced more actively for specific groups (see e.g. Ref. [94]). In particular, homes that are still dependent on a single fuel, particularly oil or electricity that are prone to aggressive market price fluctuations might make these households energy vulnerable. On the other end, we found that most hybrid arrangements (with four, five or six different energy technologies) were reported by male respondents. Our findings indicate that gender differences might be significant which also requires further research attention.

5.3. Classification problems and policy implications

Our analysis indicates that whilst the share of fossil-based energy sources has dramatically diminished, the uptake of renewables has not resulted in a simple replacement pattern assumed in renewable growth scenarios and country studies [24–27]. This indicates that there is a considerable group of households that lie beyond the traditional primary–supplementary thinking about heating. Our findings thus indicate that updating residential heating classification practices is timely. The current reliance on 'primary heating system' as the basis for classification invisibilizes hybrid heaters [8]. This can be consequential. For example, while heat pumps, district heating, and solar technologies are seen as integral parts of future heating arrangements, hybrid heating arrangements are largely absent in the EU's central decarbonization targets [15,95].

Residential heating classifications and statistics need to be updated to include questions about several heating systems and their interrelations, which would feed directly to Finland's and the EU's decarbonization aims by visibilizing practical measures already taken and those still necessary to facilitate the energy transition in the residential sector. Although many homeowners can identify their most important heating energy technology and while the 'primary heating' thinking simplifies calculation and analysis (for e.g. national-level fuel consumption [16]), assuming global applicability might produce inaccurate results within and between countries. Our recommendation might complicate the comparability between countries, yet this should not be a reason to exclude hybrid heating arrangements from consideration. Classification, and official statistics, are often seen as facts about the world [73]. They are powerful ordering techniques that carry political weight, inform societal problems and solution definitions [96], while policies are based on them [97]. S-RET adoption, and the manner by which it is done by households, can be rapidly progressing which requires an up-to-date basis for setting policy measures towards low carbon targets.

Similarly, under the conditions of additive uptake of renewables, support and aid mechanisms that are formulated with the focus on single technologies or fuels, or assumptions on their extent of use, might be misdirected and wrongly designed. An example of this is the Finnish state-granted one-time energy crisis aid during winter 2022/2023 whose formulation assumed wide-spread reliance of direct electricity heating based on Finnish statistics. The programme included admitting grants automatically for households with high electricity bills. Research has found out that the grant programme benefited the wealthiest sections of the Finnish population [98] simply because they use more electricity than others [99], making the grant poorly directed. In our survey direct electric heating appeared alone in domestic space-heating only in few cases (1.8 % of respondents).

It is also worthwhile to assess the position of programmes that seek to reduce CO_2 emissions by a removal of a single technology. In our dataset, several homes have retained their oil boiler and added a heat pump (an AWSHP, a GSHP or an EAHP) or electric heating in parallel. We can fairly assume that in these households, the more expensive oil is used only sparingly, such as during the coldest winter days or blackouts. It would thus be sensible to discourage fossil fuel usage through other policy tools such as taxation.

Relatedly, hybridization offers potential for demand flexibility which is increasingly critical in the system level with the rising shares of intermitted wind energy [100], particularly during cold, non-windy winter days when electricity prices are hiking. In our sample, 73 % of detached houses feature a possibility to switch from electricity consuming heating (electric heating, GSHP, AWSHP and ASHP) to a technology or fuel that does not require electricity. Hybridization thus improves the technological and price related resilience at the household level, and if widespread, strengthens national energy security as well.

There are several policy measures that can support the proliferation of hybrid heating arrangements and optimizing the carbon reductions achieved through them. Currently few private companies offer integrated hybrid solutions or planning services for hybrid arrangements for detached houses in Finland (to our knowledge, such services are scarce also elsewhere), nor does the public energy counselling provide encompassing support on hybrid energy technologies. Consequently, many S-RET adopters turn to peer-to-peer Internet communities to select, purchase, integrate, run, and troubleshoot these systems [23,46,90]. This state of the affairs could be rectified through support measures targeted at planners and installers of hybrid heating arrangements as well as at companies developing digital automation systems that help further optimize multiple heating systems. Open hardware and open APIs in S-RETs and automation systems would be further conducive to the integration and set-up of integrated heating arrangements, and steps towards achieving this can be taken both through regulation and through support to open innovation communities. Public energy counselling could also provide information about the possibilities of hybrid heating and elevate the accessibility of information on hybrid heating for example through targeted advisory and more diverse portfolios of media through which these services are offered.

5.4. Limitations and suggestions for further research

Despite our dataset being large, it was non-representative of the Finnish population. Therefore, our findings, particularly considering the prevalence of various energy systems, should be taken as indicative. Survey responses were self-reported and therefore some errors may have remained despite our systematic identification of unreliable responses. Whilst our findings correlate with the gross installation numbers of heating technologies in Finnish detached houses that are twice the number of houses, we might have captured a more progressive set of respondents regarding the energy transition than that of an average Finnish detached house owner. Our respondent base (somewhat more educated and mid-income, emphasis on South of Finland; majority being a homeowner association members) may therefore be ahead in the adoption of S-RETs, but there is no reason to assume that the adoption of S-RET will, in the future, be slowed down. What our study is able to imply that there exists a phenomenon of additive adoption of S-RET systems by the respondent homeowners, instead of replacing adoption. Thus, even if the resulting hybridization of installations is not fully representative, it indicates an ongoing development.

Further surveys on household-level energy technology diffusion are needed due to insufficient granularity on the topic in official statistics databases. Survey questions are recommended to also capture local level details on available infrastructures and energy prices which evidently impacts homeowners' motivation to install alternative or ancillary heating systems. For example, district heating prices vary significantly across municipalities in Finland [101]. In addition, it would be important to explore *how* various hybrid heating arrangements are utilized by households, calling for more in-depth qualitative studies. As heating arrangements are major determinants of energy poverty in Nordic countries [78,102], the extent and qualities that hybrid heating arrangements may have in energy poverty alleviation requires more research. At the same time, it would be important to further investigate the role of hybrid heating in low carbon transitions, as hybridization can also sometimes act as a barrier to more comprehensive consumption-reducing building renovations or energy renovations that might be necessary in the energy transition.

6. Conclusion

Our study focused on hybridization in domestic space-heating basing on a large survey-data in Finland. Our results indicate that the energy transition in detached housing in Finland was not about 'replacing' the old, traditional heating system, such as oil-based or wood-based boiler but by now have come to include the adding of new energy units, particularly various heat-pumps on top, or integrating them within the existing heating arrangements. The resulting hybrid heating arrangements are highly diverse and very common in our sample. Hybridization in heating is broad-reached, and considers households from various socio-demographic backgrounds, geographic regions, and buildings of all ages. Unfortunately, this hybrid nature in heating and heating practices is not captured by official statistics that require each building's energy consumption be categorized into just one energy source category. Energy and climate policy should also feature targeted actions addressing this multi-faceted heating reality in the domestic sector towards greener, and more energy just futures.

CRediT authorship contribution statement

Sini Numminen: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing, Project administration, Data curation, Funding acquisition. **Marika Silvikko de Villafranca:** Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Sampsa Hyysalo:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2024.101435.

Appendix A

Table A.1
Statistics of respondents with different numbers of energy technologies or fuels used

Variable		Number of respondents: All sample 4276 respondents	1 energy technology 486 (11.4 %)	2 energy technologies 1620 (37.9 %)	3 energy technologies 1745 (40.8 %)	4–6 energy technologies 425 (9.9 %)	Number of technologies: Mean	SD
age	1 18-29	33 (0.8 %)	6 (1.2 %)	17 (1.0 %)	9 (0.5 %)	1 (0.2 %)	2.15	0.76
	2 30-34	135 (3.2 %)	9 (1.9 %)	50 (3.1 %)	67 (3.8 %)	9 (2.1 %)	2.57	0.74
	3 35-39	226 (5.3 %)	24 (4.9 %)	84 (5.2 %)	104 (6.0 %)	14 (3.3 %)	2.48	0.77
	4 40-44	335 (7.8 %)	36 (7.4 %)	131 (8.1 %)	139 (8.0 %)	29 (6.8 %)	2.49	0.83
	5 45-59	323 (7.6 %)	29 (6.0 %)	106 (6.5 %)	154 (8.8 %)	34 (8.0 %)	2.61	0.82
	6 50-54	449 (10.5 %)	43 (8.8 %)	185 (11.4 %)	176 (10.1 %)	45 (10.6 %)	2.50	0.81
	7 55-59	517 (12.1 %)	61 (12.6 %)	216 (13.3 %)	204 (11.7 %)	36 (8.5 %)	2.42	0.80
	8 60-64	549 (12.8 %)	66 (13.6 %)	211 (13.0 %)	220 (12.6 %)	52 (12.2 %)	2.48	0.86
	9 65-69	681 (15.9 %)	78 (16.0 %)	237 (14.6 %)	293 (16.8 %)	73 (17.2 %)	2.54	0.85
	10 70-74	588 (13.8 %)	61 (12.6 %)	210 (13.0 %)	237 (13.6 %)	80 (18.8 %)	2.59	0.88
	11 75-79	310 (7.2 %)	50 (10.3 %)	121 (7.5 %)	101 (5.8 %)	38 (8.9 %)	2.42	0.92
	12 80-	130 (3.0 %)	23 (4.7 %)	52 (3.2 %)	41 (2.3 %)	14 (3.3 %)	2.38	0.97
age (in 10 categories)	1 18-34	168 (3.9 %)	15 (3.1 %)	67 (4.1 %)	76 (4.4 %)	10 (2.4 %)	2.49	0.76
	2 35-39	226 (5.3 %)	24 (4.9 %)	84 (5.2 %)	104 (6.0 %)	14 (3.3 %)	2.48	0.77
	3 40-44	335 (7.8 %)	36 (7.4 %)	131 (8.1 %)	139 (8.0 %)	29 (6.8 %)	2.49	0.83
	4 45-59	323 (7.6 %)	29 (6.0 %)	106 (6.5 %)	154 (8.8 %)	34 (8.0 %)	2.61	0.82

(continued on next page)

Table A.1 (*continued*)

Variable		Number of respondents: All sample 4276 respondents	1 energy technology 486 (11.4 %)	2 energy technologies 1620 (37.9 %)	3 energy technologies 1745 (40.8 %)	4–6 energy technologies 425 (9.9 %)	Number of technologies: Mean	SD
	5 50-54	449 (10.5 %)	43 (8.8 %)	185 (11.4 %)	176 (10.1 %)	45 (10.6 %)	2.50	0.81
	6 55-59	517 (12.1 %)	61 (12.6 %)	216 (13.3 %)	204 (11.7 %)	36 (8.5 %)	2.42	0.80
	7 60-64	549 (128 %)	66 (13.6 %)	211 (13.0 %)	220 (12.6 %)	52 (12.2 %)	2.48	0.86
	8 65-69	681 (15.9 %)	78 (16.0 %)	237 (14.6 %)	293 (16.8 %)	73 (17.2 %)	2.54	0.85
	9 70-74	588 (13.8 %)	61 (12.6 %)	210 (13.0 %)	237 (13.6 %)	80 (18.8 %)	2.59	0.88
	10 75-	440 (10.3 %)	73 (15.0 %)	173 (10.7 %)	142 (8.1 %)	52 (12.2 %)	2.41	0.94
income	Less than 12000 €	98 (2.3 %)	9 (1.9 %)	37 (2.3 %)	45 (2.6 %)	7 (1.6 %)	2.52	0.79
	12000-14400 €	102 (2.4 %)	13 (2.7 %)	43 (2.7 %)	39 (2.2 %)	7 (1.6 %)	2.39	0.80
	14400-20400 €	181 (4.2 %)	28 (5.8 %)	83 (5.1 %)	57 (3.3 %)	13 (3.1 %)	2.31	0.83
	20400-27600 €	415 (9.7 %)	63 (13.0 %)	161 (9.9 %)	151 (8.7 %)	40 (9.4 %)	2.41	0.87
	27600-42000 €	1116 (26.1 %)	141 (29.0 %)	415 (25.6 %)	454 (26.0 %)	106 (24.9 %)	2.48	0.85
	42000-63600 €	1501 (35.1 %)	152 (31.3 %)	552 (34.1 %)	626 (35.9 %)	171 (40.2 %)	2.56	0.85
	63600-80400 €	524 (12.3 %)	50 (10.3 %)	197 (12.2 %)	228 (13.1 %)	49 (11.5 %)	2.54	0.82
	80400-104400 €	215 (5.0 %)	19 (3.9 %)	79 (4.9 %)	96 (5.5 %)	21 (4.9 %)	2.57	0.82
	104400-132000 €	83 (1.9 %)	8 (1.6 %)	31 (1.9 %)	35 (2.0 %)	9 (2.1 %)	2.54	0.82
	over 132000 €	41 (1.0 %)	3 (0.6 %)	22 (1.4 %)	14 (0.8 %)	2 (0.5 %)	2.37	0.70
wregion[a])	South-west	2671 (62.5 %)	296 (60.9 %)	1005 (62.0 %)	1091 (62.5 %)	279 (65.6 %)	2.52	0.86
	Central	881 (20.6 %)	99 (20.4 %)	318 (19.6 %)	367 (21.0 %)	97 (22.8 %)	2.53	0.84
	Northern Central	586 (13.7 %)	68 (14.0 %)	231 (14.3 %)	243 (13.9 %)	44 (10.4 %)	2.45	0.79
	North	138 (3.2 %)	23 (4.7 %)	66 (4.1 %)	44 (2.5 %)	5 (1.2 %)	2.22	0.76
gender	Male	2715 (63.5 %)	283 (58.2 %)	986 (60.9 %)	1124 (64.4 %)	322 (75.8 %)	2.56	0.86
	Female	1561 (36.5 %)	203 (41.8 %)	634 (39.1 %)	621 (35.6 %)	103 (24.2 %)	2.40	0.81
education	Basic	204 (4.8 %)	28 (5.8 %)	79 (4.9 %)	77 (4.4 %)	20 (4.7 %)	2.44	0.86
	Upper secondary	1506 (35.2 %)	175 (36.0 %)	603 (37.2 %)	593 (34.0 %)	135 (31.8 %)	2.46	0.83
	Lower tertiary	1394 (32.6 %)	136 (28.0 %)	503 (31.0 %)	603 (34.6 %)	152 (35.8 %)	2.56	0.83
	Higher tertiary	1064 (24.9 %)	140 (28.8 %)	396 (24.4 %)	428 (24.5 %)	100 (23.5 %)	2.47	0.87
	Postgraduate	108 (2.5 %)	7 (1.4 %)	39 (2.4 %)	44 (2.5 %)	18 (4.2 %)	2.69	0.85
education (in two cat)	Lower education	3104 (72.6 %)	339 (69.8 %)	1185 (73.1 %)	1273 (73.0 %)	307 (72.2 %)	2.51	0.83
	Higher education[b]	1172 (27.4 %)	147 (30.2 %)	435 (26.9 %)	472 (27.0 %)	118 (27.8 %)	2.49	0.87
familysize	1	626 (14.6 %)	93 (19.1 %)	268 (16.5 %)	220 (12.6 %)	45 (10.6 %)	2.35	0.83
	2	2396 (56.0 %)	246 (50.6 %)	901 (55.6 %)	980 (56.2 %)	269 (63.3 %)	2.54	0.85
	3	532 (12.4 %)	61 (12.6 %)	196 (12.1 %)	230 (13.2 %)	45 (10.6 %)	2.49	0.82
	4	489 (11.4 %)	59 (12.1 %)	178 (11.0 %)	206 (11.8 %)	46 (10.8 %)	2.50	0.85
	5	178 (4.2 %)	20 (4.1 %)	54 (3.3 %)	87 (5.0 %)	17 (4.0 %)	2.57	0.83
	6	55 (1.3 %)	7 (1.4 %)	23 (1.4 %)	22 (1.3 %)	3 (0.7 %)	2.40	0.83
employment	1 Entrepreneur	210 (4.9 %)	21 (4.3 %)	67 (4.1 %)	94 (5.4 %)	28 (6.6 %)	2.62	0.85
	2 Employed	2000 (46.8 %)	207 (42.6 %)	775 (47.8 %)	852 (48.8 %)	166 (39.1 %)	2.50	0.81
	3 Unemployed	109 (2.5 %)	22 (4.5 %)	47 (2.9 %)	37 (2.1 %)	3 (0.7 %)	2.19	0.79
	4 Retired	1835 (42.9 %)	222 (45.7 %)	676 (41.7 %)	722 (41.4 %)	215 (50.6 %)	2.52	0.88
	5 Parental leave	29 (0.7 %)	3 (0.6 %)	17 (1.0 %)	8 (0.5 %)	1 (0.2 %)	2.24	0.69
	6 Student	39 (0.9 %)	5 (1.0 %)	13 (0.8 %)	16 (0.9 %)	5 (1.2 %)	2.59	0.99
	7 Not working	54 (1.3 %)	6 (1.2 %)	25 (1.5 %)	16 (0.9 %)	7 (1.6 %)	2.44	0.86
employment (in 5 categories)	1. Entrepreneur	210 (4.9 %)	21 (4.3 %)	67 (4.1 %)	94 (5.4 %)	28 (6.6 %)	2.62	0.85
	2 Employed	2000 (46.8 %)	207 (42.6 %)	775 (47.8 %)	852 (48.8 %)	166 (39.1 %)	2.50	0.81
	3 Unemployed	109 (2.5 %)	22 (4.5 %)	47 (2.9 %)	37 (2.1 %)	3 (0.7 %)	2.19	0.79
	4 Retired	1835 (42.9 %)	222 (45.7 %)	676 (41.7 %)	722 (41.4 %)	215 (50.6 %)	2.52	0.88
	5 Out of work	122 (2.9 %)	14 (2.9 %)	55 (3.4 %)	40 (2.3 %)	13 (3.1 %)	2.44	0.87
Wood user	1 No	952 (22.3 %)	387 (79.6 %)	478 (29.5 %)	80 (4.6 %)	7 (1.6 %)	1.69	0.65
	2 Yes	3324 (77.7 %)	99 (20.4 %)	1142 (70.5 %)	1665 (95.4 %)	418 (98.4 %)	2.73	0.75
Pellets	1 No	4209 (98.4 %)	482 (99.2 %)	1609 (99.3 %)	1725 (98.9 %)	393 (92.5 %)	2.49	0.83
	2 Yes	67 (1.6 %)	4 (0.8 %)	11 (0.7 %)	20 (1.1 %)	32 (7.5 %)	3.37	1.14
District heating	1 No	4001 (93.6 %)	411 (84.6 %)	1492 (92.1 %)	1683 (96.4 %)	415 (97.6 %)	2.54	0.84
	2 Yes	275 (6.4 %)	75 (15.4 %)	128 (7.9 %)	62 (3.6 %)	10 (2.4 %)	2.03	0.80
Gas heating	1 No	4262 (99.7 %)	484 (99.6 %)	1614 (99.6 %)	1739 (99.7 %)	425 (100.0 %)	2.50	0.85
	2 Yes	14 (0.3 %)	2 (0.4 %)	6 (0.4 %)	6 (0.3 %)		2.29	0.73
Oil user	1 No	3721 (87.0 %)	411 (84.6 %)	1409 (87.0 %)	1554 (89.1 %)	347 (81.6 %)	2.50	0.83
	2 Yes	555 (13.0 %)	75 (15.4 %)	211 (13.0 %)	191 (10.9 %)	78 (18.4 %)	2.51	0.93
Electricity heating	1 No	2188 (51.2 %)	408 (84.0 %)	1000 (61.7 %)	634 (36.3 %)	146 (34.4 %)	2.24	0.84
	2 Yes	2088 (48.8 %)	78 (16.0 %)	620 (38.3 %)	1111 (63.7 %)	279 (65.6 %)	2.78	0.76
GSHP owner	1 No	3614 (84.5 %)	367 (75.5 %)	1307 (80.7 %)	1557 (89.2 %)	383 (90.1 %)	2.55	0.84
	2 Yes	662 (15.5 %)	119 (24.5 %)	313 (19.3 %)	188 (10.8 %)	42 (9.9 %)	2.23	0.82
AWSHP owner	1 No	3894 (91.1 %)	453 (93.2 %)	1487 (91.8 %)	1596 (91.5 %)	358 (84.2 %)	2.49	0.84
	2 Yes	382 (8.9 %)	33 (6.8 %)	133 (8.2 %)	149 (8.5 %)	67 (15.8 %)	2.68	0.92
ASHP owner	1 No	1756 (41.1 %)	483 (99.4 %)	1033 (63.8 %)	219 (12.6 %)	21 (4.9 %)	1.87	0.66
	2 Yes	2520 (58.9 %)	3 (0.6 %)	587 (36.2 %)	1526 (87.4 %)	404 (95.1 %)	2.94	0.67
EAHP owner	1 No	4031 (94.3 %)	486 (100.0 %)	1565 (96.6 %)	1636 (93.8 %)	344 (80.9 %)	2.46	0.83
	2 Yes	245 (5.7 %)		55 (3.4 %)	109 (6.2 %)	81 (19.1 %)	3.16	0.84

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Table A.1 (*continued*)

Variable		Number of respondents: All sample 4276 respondents	1 energy technology 486 (11.4 %)	2 energy technologies 1620 (37.9 %)	3 energy technologies 1745 (40.8 %)	4–6 energy technologies 425 (9.9 %)	Number of technologies: Mean	SD
PV owner	1 No	3752 (87.7 %)	486 (100.0 %)	1581 (97.6 %)	1556 (89.2 %)	129 (30.4 %)	2.36	0.75
	2 Yes	524 (12.3 %)		39 (2.4 %)	189 (10.8 %)	296 (69.6 %)	3.56	0.73
Solar collector owner	1 No	4209 (98.4 %)	486 (100.0 %)	1615 (99.7 %)	1721 (98.6 %)	387 (91.1 %)	2.48	0.83
	2 Yes	67 (1.6 %)		5 (0.3 %)	24 (1.4 %)	38 (8.9 %)	3.67	0.86
buildingyear		Mean (sd): 1979.35 (25.57) min < med < max: 1750 < 1983 < 2022	Mean (sd): 1977.58 (25.28) min < med < max: 1820 < 1979.5 < 2022	Mean (sd): 1979.722 (25.74) min < med < max: 1750 < 1982 < 2022	Mean (sd): 1979.32 (25.57) min < med < max: 1800 < 1985 < 2022	Mean (sd): 1980.09 (25.21) min < med < max: 1820 < 1984 < 2022		
floorarea		Mean (sd): 153.80 (59.03) min < med < max: 8 < 142 < 810	Mean (sd): 153.12 (58.85) min < med < max: 8 < 140 < 446	Mean (sd): 154.76 (61.45) min < med < max: 20 < 143.5 < 810	Mean (sd): 151.14 (55.73) min < med < max: 40 < 140 < 606	Mean (sd): 161.83 (62.24) min < med < max: 65 < 150 < 600		

[a] Counties Uusimaa, Southwest Finland, Satakunta and Åland were categorized in 'South-west'; Kanta-Häme, Pirkanmaa, Päijät-Häme, Kymenlaakso, South Karelia, South Savo, South Ostrobothnia, Central Ostrobothnia in 'Central'; North Savo, North Karelia, Central Finland and Ostrobothnia in 'Northern Central' and; North Ostrobothnia, Kainuu and Lapland in 'North'.

[b] A master's degree or higher.

Table A.2
162 Identified heating arrangements and their commonality

Count	Popularity order	Heating Arrangements	Detached houses (N = 4276)	Share of houses
1	1	Wood, Electric heating, ASHP	982	23.0 %
2	2	Wood, Electric heating	401	9.4 %
3	3	Wood, GSHP	230	5.4 %
4	4	Electric heating, ASHP	196	4.6 %
5	5	Wood, ASHP	183	4.3 %
6	6	Wood, Electric heating, ASHP, PV	152	3.6 %
7	7	GSHP	118	2.8 %
8	8	Wood, Oil, ASHP	115	2.7 %
9	9	Wood, GSHP, ASHP	114	2.7 %
10	10	Wood, Oil	110	2.6 %
11	11	Wood	99	2.3 %
12	12	Wood, District heating	85	2.0 %
13	13	Wood, AWSHP, ASHP	82	1.9 %
14	14	Electric heating	78	1.8 %
15	15	District heating	74	1.7 %
16	16	Oil	73	1.7 %
17	17	Wood, AWSHP	69	1.6 %
18	18	Oil, ASHP	64	1.5 %
19	19	GSHP, ASHP	58	1.4 %
20	20	Wood, District heating, ASHP	54	1.3 %
21	21	Wood, ASHP, PV	49	1.1 %
22	22	AWSHP, ASHP	42	1.0 %
23	23	Wood, Electric heating, ASHP, EAHP	41	1.0 %
24	25	Wood, Electric heating, EAHP	39	0.9 %
25	25	Wood, GSHP, PV	39	0.9 %
26	24	Wood, ASHP, EAHP	38	0.9 %
27	24	District heating, ASHP	38	0.9 %
28	26	Wood, EAHP	36	0.8 %
29	27	AWSHP	33	0.8 %
30	28	Wood, Electric heating, PV	28	0.7 %
31	29	Wood, GSHP, ASHP, PV	27	0.6 %
32	30	Wood, AWSHP, ASHP, PV	26	0.6 %
33	31	Wood, Oil, Electric heating, ASHP	25	0.6 %
34	32	Wood, Oil, Electric heating	22	0.5 %
35	32	Electric heating, ASHP, PV	22	0.5 %
36	33	GSHP, PV	19	0.4 %
37	34	Wood, Oil, AWSHP	17	0.4 %
38	35	Wood, Oil, AWSHP, ASHP	16	0.4 %
39	35	Oil, AWSHP	16	0.4 %
40	36	Electric heating, EAHP	14	0.3 %
41	37	Wood, Pellets, Electric heating, ASHP	13	0.3 %
42	37	Wood, AWSHP, PV	13	0.3 %
43	37	Oil, AWSHP, ASHP	13	0.3 %
44	38	GSHP, ASHP, PV	11	0.3 %
45	39	Wood, Electric heating, ASHP, EAHP, PV	9	0.2 %
46	40	Wood, Pellets, Electric heating, ASHP, PV	8	0.2 %
47	40	Wood, Pellets, ASHP	8	0.2 %

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Table A.2 (*continued*)

Count	Popularity order	Heating Arrangements	Detached houses (N = 4276)	Share of houses
48	40	Wood, District heating, ASHP, PV	8	0.2 %
49	40	Wood, Oil, ASHP, PV	8	0.2 %
50	40	Wood, ASHP, EAHP, PV	8	0.2 %
51	40	Wood, PV	8	0.2 %
52	41	Wood, Electric heating, ASHP, Solar thermal	7	0.2 %
53	42	Wood, Pellets	6	0.1 %
54	42	Wood, Electric heating, ASHP, PV, Solar thermal	6	0.1 %
55	42	Wood, GSHP, EAHP	6	0.1 %
56	42	Wood, AWSHP, Solar thermal	6	0.1 %
57	42	Oil, Electric heating	6	0.1 %
58	42	Electric heating, ASHP, EAHP	6	0.1 %
59	43	Wood, Electric heating, EAHP, PV	5	0.1 %
60	43	Wood, EAHP, PV	5	0.1 %
61	43	AWSHP, ASHP, PV	5	0.1 %
62	44	Wood, Pellets, ASHP, PV	4	0.1 %
63	44	Wood, Gas heating, ASHP	4	0.1 %
64	44	Wood, Gas heating	4	0.1 %
65	44	Wood, Oil, GSHP, ASHP	4	0.1 %
66	44	Wood, ASHP, PV, Solar thermal	4	0.1 %
67	44	Pellets	4	0.1 %
68	44	Oil, Electric heating, ASHP	4	0.1 %
69	44	AWSHP, PV	4	0.1 %
70	45	Wood, Pellets, Oil	3	0.1 %
71	45	Wood, Pellets, AWSHP	3	0.1 %
72	45	Wood, District heating, EAHP	3	0.1 %
73	45	Wood, Oil, AWSHP, ASHP, PV	3	0.1 %
74	45	Wood, Oil, AWSHP, PV	3	0.1 %
75	45	Wood, Oil, EAHP	3	0.1 %
76	45	Wood, Oil, PV	3	0.1 %
77	45	Wood, Oil, Solar thermal	3	0.1 %
78	45	Wood, GSHP, Solar thermal	3	0.1 %
79	45	Wood, PV, Solar thermal	3	0.1 %
80	45	Wood, Solar thermal	3	0.1 %
81	45	Oil, PV	3	0.1 %
82	45	Electric heating, PV	3	0.1 %
83	45	GSHP, ASHP, EAHP	3	0.1 %
84	45	ASHP	3	0.1 %
85	46	Wood, Pellets, Electric heating	2	0.0 %
86	46	Wood, Pellets, GSHP, ASHP	2	0.0 %
87	46	Wood, Pellets, GSHP	2	0.0 %
88	46	Wood, Pellets, PV	2	0.0 %
89	46	Wood, District heating, Oil	2	0.0 %
90	46	Wood, District heating, PV	2	0.0 %
91	46	Wood, Oil, Electric heating, AWSHP, ASHP	2	0.0 %
92	46	Wood, Oil, Electric heating, AWSHP	2	0.0 %
93	46	Wood, Oil, GSHP, ASHP, PV	2	0.0 %
94	46	Wood, Oil, GSHP	2	0.0 %
95	46	Wood, Oil, AWSHP, Solar thermal	2	0.0 %
96	46	Wood, Oil, ASHP, EAHP	2	0.0 %
97	46	Wood, Oil, ASHP, Solar thermal	2	0.0 %
98	46	Wood, Electric heating, Solar thermal	2	0.0 %
99	46	Wood, GSHP, AWSHP	2	0.0 %
100	46	Wood, GSHP, ASHP, EAHP	2	0.0 %
101	46	Wood, GSHP, ASHP, Solar thermal	2	0.0 %
102	46	Wood, GSHP, PV, Solar thermal	2	0.0 %
103	46	Wood, AWSHP, ASHP, EAHP, PV	2	0.0 %
104	46	Wood, AWSHP, ASHP, PV, Solar thermal	2	0.0 %
105	46	Wood, AWSHP, ASHP, Solar thermal	2	0.0 %
106	46	Wood, ASHP, Solar thermal	2	0.0 %
107	46	Pellets, Electric heating, ASHP	2	0.0 %
108	46	District heating, Oil, ASHP	2	0.0 %
109	46	Gas heating	2	0.0 %
110	46	Oil, AWSHP, ASHP, PV	2	0.0 %
111	46	Oil, ASHP, Solar thermal	2	0.0 %
112	46	Oil, EAHP	2	0.0 %
113	46	Electric heating, ASHP, EAHP, PV	2	0.0 %
114	46	GSHP, EAHP	2	0.0 %
115	46	GSHP, PV, Solar thermal	2	0.0 %
116	46	GSHP, Solar thermal	2	0.0 %
117	47	Wood, Pellets, Oil, ASHP, Solar thermal	1	0.0 %
118	47	Wood, Pellets, Electric heating, ASHP, EAHP, PV	1	0.0 %
119	47	Wood, Pellets, Electric heating, ASHP, EAHP	1	0.0 %
120	47	Wood, Pellets, GSHP, ASHP, PV	1	0.0 %
121	47	Wood, Pellets, ASHP, EAHP, PV	1	0.0 %
122	47	Wood, Pellets, Solar thermal	1	0.0 %
123	47	Wood, District heating, AWSHP	1	0.0 %

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Table A.2 (*continued*)

Count	Popularity order	Heating Arrangements	Detached houses (N = 4276)	Share of houses
124	47	Wood, District heating, ASHP, EAHP	1	0.0 %
125	47	Wood, District heating, EAHP, PV	1	0.0 %
126	47	Wood, Gas heating, AWSHP	1	0.0 %
127	47	Wood, Oil, Electric heating, ASHP, PV	1	0.0 %
128	47	Wood, Oil, Electric heating, ASHP, Solar thermal	1	0.0 %
129	47	Wood, Oil, Electric heating, PV	1	0.0 %
130	47	Wood, Oil, GSHP, AWSHP	1	0.0 %
131	47	Wood, Oil, AWSHP, PV, Solar thermal	1	0.0 %
132	47	Wood, Oil, ASHP, PV, Solar thermal	1	0.0 %
133	47	Wood, Oil, PV, Solar thermal	1	0.0 %
134	47	Wood, GSHP, AWSHP, ASHP	1	0.0 %
135	47	Wood, GSHP, ASHP, PV, Solar thermal	1	0.0 %
136	47	Wood, GSHP, EAHP, PV	1	0.0 %
137	47	Wood, GSHP, EAHP, Solar thermal	1	0.0 %
138	47	Wood, AWSHP, ASHP, EAHP	1	0.0 %
139	47	Wood, AWSHP, EAHP, PV	1	0.0 %
140	47	Wood, AWSHP, EAHP	1	0.0 %
141	47	Pellets, Oil, ASHP	1	0.0 %
142	47	Pellets, ASHP	1	0.0 %
143	47	District heating, Oil	1	0.0 %
144	47	District heating, ASHP, EAHP	1	0.0 %
145	47	District heating, ASHP, PV	1	0.0 %
146	47	District heating, PV	1	0.0 %
147	47	Gas heating, AWSHP, ASHP	1	0.0 %
148	47	Gas heating, AWSHP	1	0.0 %
149	47	Gas heating, ASHP	1	0.0 %
150	47	Oil, Electric heating, AWSHP, ASHP	1	0.0 %
151	47	Oil, Electric heating, AWSHP	1	0.0 %
152	47	Oil, Electric heating, PV	1	0.0 %
153	47	Oil, GSHP	1	0.0 %
154	47	Oil, AWSHP, PV	1	0.0 %
155	47	Oil, ASHP, EAHP, Solar thermal	1	0.0 %
156	47	Oil, ASHP, EAHP	1	0.0 %
157	47	Electric heating, ASHP, PV, Solar thermal	1	0.0 %
158	47	GSHP, EAHP, PV	1	0.0 %
159	47	AWSHP, ASHP, EAHP	1	0.0 %
160	47	AWSHP, EAHP	1	0.0 %
161	47	ASHP, EAHP, PV	1	0.0 %
162	47	ASHP, PV	1	0.0 %

Table A.3
User Numbers of Fuel Sources and Energy Technologies, and their appearance in unique energy system arrangements

Fuel or energy technology	Detached houses (N = 4276)	Share of houses	N appearance in unique arrangements
Wood	3324	78 %	104
Air Source Heat Pump (ASHP)	2520	59 %	82
Direct Electric Heating	2088	49 %	37
Ground Source Heat Pump (GSHP)	662	15 %	31
Oil Heating	555	13 %	50
Solar PV	524	12 %	58
Air Water Source Heat Pump (AWSHP)	382	9 %	39
District Heating	275	6 %	16
Exhaust Air Heat Pump (EAHP)	245	6 %	37
Solar Thermal	67	2 %	29
Pellets	67	2 %	21
Gas Heating	14	0 %	7

References

[1] IEA. World Energy Outlook 2022, International Energy Agency, 2022. https://www.iea.org/reports/world-energy-outlook-2022.

[2] J. Räihä, E. Ruokamo, Determinants of supplementary heating system choices and adoption consideration in Finland, Energy Build. 251 (2021) 111366, https://doi.org/10.1016/j.enbuild.2021.111366.

[3] EC, European Green Deal: Commission proposes to boost renovation and decarbonisation of buildings, Eur. Community (2021). https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683. (Accessed 30 June 2023).

[4] W. Wrapson, P. Devine-Wright, 'Domesticating' low carbon thermal technologies: diversity, multiplicity and variability in older person, off grid households, Energy Pol. 67 (2014) 807–817, https://doi.org/10.1016/j.enpol.2013.11.078.

[5] R. Chard, G. Walker, Living with fuel poverty in older age: Coping strategies and their problematic implications, Energy Research & Social Science 18 (2016) 62–70, https://doi.org/10.1016/j.erss.2016.03.004.

[6] E. Heiskanen, K. Matschoss, Understanding the uneven diffusion of building-scale renewable energy systems: a review of household, local and country level factors in diverse European countries, Renew. Sustain. Energy Rev. 75 (2017) 580–591, https://doi.org/10.1016/j.rser.2016.11.027.

[7] E. Roberts, Warming with wood: Exploring the everyday heating practices of rural off-gas households in Wales, Energy Pol. 142 (2020) 111451, https://doi.org/10.1016/j.enpol.2020.111451.

[8] S. Numminen (ed.), ASSIST consortium, ASSIST Final report on Home Energy Advisor (HEA) network activity on saved energy and increased comfort level, H2020 project Assist2gether (2020). https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d4a7a571&appId=PPGMS.

[9] E. Zeyen, V. Hagenmeyer, T. Brown, Mitigating heat demand peaks in buildings in a highly renewable European energy system, Energy 231 (2021) 120784, https://doi.org/10.1016/j.energy.2021.120784.
[10] J. Rinkinen, M. Jalas, Moving home: houses, new occupants and the formation of heating practices, Build. Res. Inf. 45 (2017) 293–302, https://doi.org/10.1080/09613218.2016.1143299.
[11] S. Nyborg, I. Røpke, Heat pumps in Denmark—from ugly duckling to white swan, Energy Res. Social Sci. 9 (2015) 166–177, https://doi.org/10.1016/j.erss.2015.08.021.
[12] A.S. Gaur, D.Z. Fitiwi, J. Curtis, Heat pumps and our low-carbon future: a comprehensive review, Energy Res. Social Sci. 71 (2021) 101764, https://doi.org/10.1016/j.erss.2020.101764.
[13] J.K. Juntunen, Domestication pathways of small-scale renewable energy technologies, Sustain Sci Pract Policy Phila 10 (2014), https://doi.org/10.1080/15487733.2014.11908130.
[14] EU, MEPs Back Plans for a Climate Neutral Building Sector by 2050 | News, European Parliament, 2023. https://www.europarl.europa.eu/news/en/press-room/20230310IPR77228/meps-back-plans-for-a-climate-neutral-building-sector-by-2050. (Accessed 30 June 2023).
[15] D. Peters, K. van der Leun, W. Terlouw, J. van Tilburg, T. Berg, M. Schimmel, I. van der Hoorn, M. Buseman, M. Staats, M. Schenkel, G. Ur, R. Mir, Gas decarbonisation pathways 2020–2050, Gas for Climate,, 2020. https://www.europeanbiogas.eu/wp-content/uploads/2020/04/Gas-for-Climate-Gas-Decarbonisation-Pathways-2020-2050.pdf.
[16] G. Martinopoulos, K.T. Papakostas, A.M. Papadopoulos, A comparative review of heating systems in EU countries, based on efficiency and fuel cost, Renew. Sustain. Energy Rev. 90 (2018) 687–699, https://doi.org/10.1016/j.rser.2018.03.060.
[17] Eurostat (European Commission). Manual for Statistics on Energy Consumption in Households, Publications Office of the European Union, 2013. https://ec.europa.eu/eurostat/documents/3859598/5935825/KS-GQ-13-003-EN.PDF/baa96509-3f4b-4c7a-94dd-feb1a31c7291.
[18] Office for national statistics of UK, Energy efficiency of housing in England and Wales: 2021. https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/energyefficiencyofhousinginenglandandwales/2021#central-heating-fuel-type-for-dwellings, 2021.
[19] Central Statistics Office of Ireland, Domestic Building Energy Ratings Quarter 3 2022 - CSO - Central Statistics Office (2022). https://www.cso.ie/en/releasesandpublications/ep/p-dber/domesticbuildingenergyratingsquarter32022/. (Accessed 30 June 2023).
[20] Statistics Finland, 13qk – Main heating mode of the dwelling by type of building, 2012-2022. (part on the main statistics Households' consumption – Kotitalouksien kulutus. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__ktutk/statfin_ktutk_pxt_13qk.px/, 2022. (Accessed 15 January 2023).
[21] Statistics Finland, 115y – Household-dwelling units and dwelling population by tenure status, type of building and number of rooms in 2022. (part on the main statistics Dwellings and housing conditions – Asunnot ja asuinolot). https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__asas/statfin_asas_pxt_115y.px, 2022. (Accessed 11 April 2024).
[22] M. Jalas, J. Rinkinen, Stacking wood and staying warm: time, temporality and housework around domestic heating systems, J. Consum. Cult. 16 (2016) 43–60, https://doi.org/10.1177/1469540513509639.
[23] S. Hyysalo, Citizen Activities in Energy Transition: User Innovation, New Communities, and the Shaping of a Sustainable Future, Routledge, London, 2021, https://doi.org/10.4324/9781003133919.
[24] International Energy Agengy (IEA), Energy Technology Perspectives 2023 – Analysis, IEA, 2023. https://www.iea.org/reports/energy-technology-perspectives-2023. (Accessed 30 June 2023).
[25] H.-B. Duan, L. Zhu, Y. Fan, A cross-country study on the relationship between diffusion of wind and photovoltaic solar technology, Technol. Forecast. Soc. Change 83 (2014) 156–169, https://doi.org/10.1016/j.techfore.2013.07.005.
[26] Y. Yamaguchi, K. Akai, J. Shen, N. Fujimura, Y. Shimoda, T. Saijo, Prediction of photovoltaic and solar water heater diffusion and evaluation of promotion policies on the basis of consumers' choices, Appl. Energy 102 (2013) 1148–1159, https://doi.org/10.1016/j.apenergy.2012.06.037.
[27] J. van Wijk, I. Fischhendler, The effect of institutional memory on the diffusion of wind energy, Environ. Innov. Soc. Transit. 45 (2022) 318–336, https://doi.org/10.1016/j.eist.2022.11.006.
[28] U. Dewald, B. Truffer, Market Formation in technological innovation systems—diffusion of photovoltaic Applications in Germany, Ind. Innovat. 18 (2011) 285–300, https://doi.org/10.1080/13662716.2011.561028.
[29] U. Dewald, B. Truffer, The local sources of market formation: Explaining regional growth Differentials in German photovoltaic markets, Eur. Plann. Stud. 20 (2012) 397–420, https://doi.org/10.1080/09654313.2012.651803.
[30] M. Ornetzeder, H. Rohracher, Of solar collectors, wind power, and car sharing: comparing and understanding successful cases of grassroots innovations, Global Environ. Change 23 (2013) 856–867, https://doi.org/10.1016/j.gloenvcha.2012.12.007.
[31] A.D. Andersen, J. Markard, Multi-technology interaction in socio-technical transitions: how recent dynamics in HVDC technology can inform transition theories, Technol. Forecast. Soc. Change 151 (2020) 119802, https://doi.org/10.1016/j.techfore.2019.119802.
[32] J. Markard, V.H. Hoffmann, Analysis of complementarities: Framework and examples from the energy transition, Technol. Forecast. Soc. Change 111 (2016) 63–75, https://doi.org/10.1016/j.techfore.2016.06.008.
[33] EHPA, European Heat Pump Market Statistics, Report 2018. Brussels, Belgium: European Heat Pump Association, 2018.
[34] EHPA, Subsidies for Residential Heat Pumps in Europe, Eur Heat Pump Assoc, 2023. https://www.ehpa.org/publications/subsidies-for-residential-heat-pumps-in-europe/. (Accessed 30 June 2023).
[35] K. Chadwick, R. Russell-Bennett, N. Biddle, The role of human influences on adoption and rejection of energy technology: a systematised critical review of the literature on household energy transitions, Energy Res. Social Sci. 89 (2022) 102528, https://doi.org/10.1016/j.erss.2022.102528.
[36] M.J. Hannon, Raising the temperature of the UK heat pump market: learning lessons from Finland, Energy Pol. 85 (2015) 369–375, https://doi.org/10.1016/j.enpol.2015.06.016.
[37] M.A. Barrera, I. Sabbatella, E. Serrani, Macroeconomic barriers to energy transition in peripheral countries: the case of Argentina, Energy Pol. 168 (2022) 113117, https://doi.org/10.1016/j.enpol.2022.113117.
[38] S. Hyysalo, E. Heiskanen, J. Lukkarinen, K. Matschoss, M. Jalas, P. Kivimaa, et al., Market intermediation and its embeddedness – lessons from the Finnish energy transition, Environ. Innov. Soc. Transit. 42 (2022) 184–200, https://doi.org/10.1016/j.eist.2021.12.004.
[39] M. Graziano, K. Gillingham, Spatial patterns of solar photovoltaic system adoption: the influence of neighbors and the built environment, J. Econ. Geogr. 15 (2015) 815–839, https://doi.org/10.1093/jeg/lbu036.
[40] M. Alipour, H. Salim, R.A. Stewart, O. Sahin, Predictors, taxonomy of predictors, and correlations of predictors with the decision behaviour of residential solar photovoltaics adoption: a review, Renew. Sustain. Energy Rev. 123 (2020) 109749, https://doi.org/10.1016/j.rser.2020.109749.
[41] C.S.E. Bale, N.J. McCullen, T.J. Foxon, A.M. Rucklidge, W.F. Gale, Harnessing social networks for promoting adoption of energy technologies in the domestic sector, Energy Pol. 63 (2013) 833–844, https://doi.org/10.1016/j.enpol.2013.09.033.
[42] S. Karjalainen, H. Ahvenniemi, Pleasure is the profit - the adoption of solar PV systems by households in Finland, Renew. Energy 133 (2019) 44–52, https://doi.org/10.1016/j.renene.2018.10.011.
[43] J. Palm, M. Tengvard, Motives for and barriers to household adoption of small-scale production of electricity: examples from Sweden, Sustain. Sci. Pract. Pol. 7 (2011) 6–15, https://doi.org/10.1080/15487733.2011.11908061.
[44] P. Murto, M. Jalas, J. Juntunen, S. Hyysalo, The difficult process of adopting a comprehensive energy retrofit in housing companies: barriers posed by nascent markets and complicated calculability, Energy Pol. 132 (2019) 955–964, https://doi.org/10.1016/j.enpol.2019.06.062.
[45] S. Hyysalo, J.K. Juntunen, S. Freeman, Internet forums and the rise of the Inventive energy user, Sci. Technol. Stud. 26 (2013) 25–51, https://doi.org/10.23987/sts.55307.
[46] S. Hyysalo, M. Johnson, J.K. Juntunen, The diffusion of consumer innovation in sustainable energy technologies, J. Clean. Prod. 162 (2017) S70–S82, https://doi.org/10.1016/j.jclepro.2016.09.045.
[47] E. Ruokamo, Household preferences of hybrid home heating systems – a choice experiment application, Energy Pol. 95 (2016) 224–237, https://doi.org/10.1016/j.enpol.2016.04.017.
[48] T.H. Meles, L. Ryan, Adoption of renewable home heating systems: an agent-based model of heat pumps in Ireland, Renew. Sustain. Energy Rev. 169 (2022) 112853, https://doi.org/10.1016/j.rser.2022.112853.
[49] E. Schulte, F. Scheller, D. Sloot, T. Bruckner, A meta-analysis of residential PV adoption: the important role of perceived benefits, intentions and antecedents in solar energy acceptance, Energy Res. Social Sci. 84 (2022) 102339, https://doi.org/10.1016/j.erss.2021.102339.
[50] E.M. Rogers, Diffusion of Innovations, fifth ed., Free Press, New York, 2003.
[51] A. Palm, Early adopters and their motives: differences between earlier and later adopters of residential solar photovoltaics, Renew. Sustain. Energy Rev. 133 (2020) 110142, https://doi.org/10.1016/j.rser.2020.110142.
[52] B. Parrish, S. Hielscher, T.J. Foxon, Consumers or users? The impact of user learning about smart hybrid heat pumps on policy trajectories for heat decarbonisation, Energy Pol. 148 (2021) 112006, https://doi.org/10.1016/j.enpol.2020.112006.
[53] C.C. Michelsen, R. Madlener, Switching from fossil fuel to renewables in residential heating systems: an empirical study of homeowners' decisions in Germany, Energy Pol. 89 (2016) 95–105, https://doi.org/10.1016/j.enpol.2015.11.018.
[54] T.H. Meles, L. Ryan, S.C. Mukherjee, Heterogeneity in preferences for renewable home heating systems among Irish households, Appl. Energy 307 (2022) 118219, https://doi.org/10.1016/j.apenergy.2021.118219.
[55] S. Caird, R. Roy, Adoption and Use of household Microgeneration heat technologies, Low Carbon Econ. 1 (2010) 61–70, https://doi.org/10.4236/lce.2010.12008.
[56] J. Rinkinen, Electricity blackouts and hybrid systems of provision: users and the "reflective practice.", Energy Sustain Soc Heidelb 3 (2013) 1–10, https://doi.org/10.1186/2192-0567-3-25.
[57] S. Karytsas, O. Polyzou, C. Karytsas, Factors affecting willingness to adopt and willingness to pay for a residential hybrid system that provides heating/cooling and domestic hot water, Renew. Energy 142 (2019) 591–603, https://doi.org/10.1016/j.renene.2019.04.108.
[58] C.C. Michelsen, R. Madlener, Homeowners' preferences for adopting innovative residential heating systems: a discrete choice analysis for Germany, Energy Econ. 34 (2012) 1271–1283, https://doi.org/10.1016/j.eneco.2012.06.009.
[59] E. Heiskanen, S. Hyysalo, M. Jalas, J. Juntunen, R. Lovio, The role of users in heating systems transitions: the case of heat pumps in Finland, in: P.

R. Christensen, S. Junginger (Eds.), Highw. Byways Radic. Innov. – Des. Perspect., 2014, pp. 169–197.
[60] Ministry of the Environment, Fossiilisesta Öljylämmityksestä Luopumisen Toimenpideohjelma, 2021. https://www.lausuntopalvelu.fi/FI/Proposal/DownloadProposalAttachment?proposalId=9cda4605-5a40-462e-a667-17e7982a7dbc&attachmentId=15521.
[61] S. Karjalainen, Thermal comfort and use of thermostats in Finnish homes and offices, Build. Environ. 44 (2009) 1237–1245, https://doi.org/10.1016/j.buildenv.2008.09.002.
[62] P. Kasanen, T.R. Lakshmanan, Residential heating choices of Finnish households, Econ. Geogr. 65 (1989) 130–145, https://doi.org/10.2307/143777.
[63] Eurostat, Homeownership Rate in Selected European Countries in 2021, by Country, Statista, 2022. https://www.statista.com/statistics/246355/home-ownership-rate-in-europe. (Accessed 5 April 2023).
[64] Statistics Finland, 11zr – heating of residential buildings by building type, 2008-2021 (part of the main statistics Energy consumption in households – Asumisen energiankulutus. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_asen/statfin_asen_pxt_11zr.px/, 2022. (Accessed 15 January 2023).
[65] Bioenergia, Puu lämmön tuotannossa – tilastot ja tekniikat (RTS Tutkimus Oy). https://www.bioenergia.fi/wp-content/uploads/2020/02/Puu-l%C3%A4mm%C3%B6n-tuotannossa-5.pdf, 2019. (Accessed 8 February 2023).
[66] Motiva, Tukilämmitysjärjestelmät (2022). https://www.motiva.fi/koti_ja_asuminen/rakentaminen/lammitysjarjestelman_valinta/tukilammitysjarjestelmat. (Accessed 8 February 2023).
[67] Sulpu, Almost 200,000 heat pumps were sold last year. An increase of 50, Suom Lämpöpumppuyhdistys Sulpu Ry (2023). https://www.sulpu.fi/almost-200000-heat-pumps-were-sold-last-year-an-increase-of-50/. (Accessed 30 June 2023).
[68] Statistics Finland, Maalämpö Yleistynyt Pääasiallisena Lämmitystapana, 2022. https://tilastokeskus.fi/julkaisu/cktwror9c4ee10b618t3njtsh. (Accessed 30 March 2023).
[69] Energy Authority, Aurinkosähkön Kapasiteetti Kasvoi Suomessa Yli 100 Megawattia Vuonna 2021, 2022. https://energiavirasto.fi/-/aurinkosahkon-kapasiteetti-kasvoi-suomessa-yli-100-megawattia-vuonna-2021.
[70] Statistics Finland, 116h – Number of buildings by intended use and heating fuel, 2021. (part on the main statistics Buildings and free-time residences – Rakennukset ja kesämökit) 2022. https://pxdata.stat.fi/PxWeb/pxweb/fi/StatFin/StatFin_rakke/statfin_rakke_pxt_116h.px. (Accessed 30 March 2022).
[71] V. Rouhiainen, Uusiutuva Energia Valtaa Alaa Pientalojen Lämmityksessä | Tieto&trendit, Statistics Finland, 2018. https://www.tilastokeskus.fi/tietotrendit/artikkelit/2018/uusiutuva-energia-valtaa-alaa-pientalojen-lammityksessa/. (Accessed 11 January 2023).
[72] Statistics Finland, Asuinrakennusten päälämmönlähteiden kehitys 2010-luvulla 2018. https://www.stat.fi/til/asen/2018/asen_2018_2019-11-21_kat_001_fi.html. (Accessed 30 March 2023).
[73] G.C. Bowker, S.L. Star, Sorting Things Out: Classification and its Consequences, MIT press, 1999.
[74] S.L. Star, G.C. Bowker, Enacting silence: residual categories as a challenge for ethics, information systems, and communication, Ethics Inf. Technol. 9 (2007) 273–280, https://doi.org/10.1007/s10676-007-9141-7.
[75] H.M. Collins, R. Evans, The third Wave of Science studies: studies of expertise and experience, Soc. Stud. Sci. 32 (2002) 235–296, https://doi.org/10.1177/0306312702032002003.
[76] Eurostat, Electricity Price Statistics, 2020.
[77] M. Ornetzeder, H. Rohracher, User-led innovations and participation processes: lessons from sustainable energy technologies, Energy Pol. 34 (2006) 138–150, https://doi.org/10.1016/j.enpol.2004.08.037.
[78] S. Numminen, T. Kajoskoski, Y. Kaltampanidis, M. Jalas, Energy vulnerability of detached home owners in Finland: an explorative study, Energy Build. 310 (2024) 114082, https://doi.org/10.1016/j.enbuild.2024.114082.
[79] Ministry of Environment. Building Code D3 Buildings and Energy Efficiency (in Finnish, original title: "D3 Suomen rakentamismääräyskokoelma. Rakennusten energiatehokkuus."), Ministry of Environment, 2011. http://www.finlex.fi/data/normit/37188-D3-2012_Suomi.pdf.
[80] Statistics Finland, Population structure – Väestörakenne, Data purchased from Statistics Finland service (2022). https://www.stat.fi/tilasto/vaerak. (Accessed 27 March 2023).
[81] Statistics Finland, Educational structure of population – Väestön koulutusrakenne, Data purchased from Statistics Finland service (2022). https://www.stat.fi/en/statistics/vkour. (Accessed 29 March 2023).
[82] Statistics Finland, Income distribution statistisics - Tulonjakotilasto, Data purchased from Statistics Finland service (2022). https://www.stat.fi/tilasto/tjt. (Accessed 27 March 2023).
[83] Statistics Finland, 116b – Household-dwelling units and dwelling population by number of persons, number of rooms and type of building, 2005-2021 (part on the main statistics Dwellings and housing conditions – Asunnot ja asuinolot). https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_asas/statfin_asas_pxt_116b.px/, 2022. (Accessed 27 March 2023).
[84] Statistics Finland, 116g – Number of buildings by intended use and year of construction, 2022. (part on the main statistics Buildings and free-time residences – Rakennukset ja kesämökit) 2022. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin_rakke/statfin_rakke_pxt_116g.px/. (Accessed 30 March 2023).
[85] N. Zumel, R.L. Thomas, J. Mount, J. Howard, Practical Data Science with R, second ed., Shelter Island, New York: Manning, 2020.
[86] A. Vallati, P. Ocłoń, C. Colucci, L. Mauri, R. de Lieto Vollaro, J. Taler, Energy analysis of a thermal system composed by a heat pump coupled with a PVT solar collector, Energy 174 (2019) 91–96, https://doi.org/10.1016/j.energy.2019.02.152.
[87] D. de Vaus, Surveys in Social Research, sixth ed., Routledge/Taylor & Francis Group, New York, NY, US, 2014.
[88] Ministry of the Environment, Rakennusten energiatalous: Määräykset ja ohjeet 1978, Suomen rakentamismääräyskokoelma D3 (1978). https://www.ymparisto.fi/download/noname/%7B4715BFC5-6BB6-466A-9ADA-39D14066A18C%7D/100783. (Accessed 11 January 2023).
[89] J. Hirvonen, Finland has become a Heat Pump Superpower. HPs produce 14 TWh/a, 16 % of the heating of Finland (80 TWh/a) according to the Finland's Country report to IEA HPC. SULPU 2023. https://www.sulpu.fi/finland-become-a-heat-pump-superpower-hps-produce-14-twh-a-16-of-the-heating-of-finland-80-twh-a-according-to-the-finlands-country-report-to-iea-hpc/. (Accessed 21 October 2023).
[90] S. Hyysalo, J.K. Juntunen, M. Martiskainen, Energy Internet forums as acceleration phase transition intermediaries, Res. Pol. 47 (2018) 872–885, https://doi.org/10.1016/j.respol.2018.02.012.
[91] Eurostat, Heating and cooling degree days - statistics 2023. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Heating_and_cooling_degree_days_-_statistics. (Accessed 21 October 2023).
[92] Ministry of the Environment, Öljylämmityksestä Luopuminen, 2023. https://ym.fi/oljylammityksesta-luopuminen. (Accessed 8 February 2023).
[93] ARA. Öljylämmityksen vaihtajalle on tarjolla useita tukimuotoja, Asumisen Rah-Ja Kehitt ARA, 2021. https://www.ara.fi/fi-FI/Ajankohtaista/Uutiset_ja_tiedotteet/Uutiset_ja_tiedotteet_2021/Oljylammityksen_vaihtajalle_on_tarjolla_(60738. (Accessed 30 June 2023).
[94] L. Sunderland, D. Gibb, Taking the Burn Out of Heating for Low-Income Households, Regulatory Assistance Project (RAP),, 2022. https://www.raponline.org/knowledge-center/taking-burn-out-of-heating-low-income-households/.
[95] F. Gerard, T. Smit, K. Rademaekers, S. Braungardt, M.E. Monejar Montagud, L. Guevara Opinska. Policy Support for Heating and Cooling Decarbonisation: Roadmap, 2021. https://op.europa.eu/en/publication-detail/-/publication/f5118ffc-eabd-11ec-a534-01aa75ed71a1/language-en.
[96] M. Alastalo, M. Åkerman, Tietokäytännöt ja hallinnan politiikka, in: M. Alastalo, M. Åkerman (Eds.), Tieto Hallinnassa Tietokäytännöt Suom, Yhteiskunnassa, Vastapaino, 2011, pp. 17–38.
[97] T. Peltola, M. Åkerman, Roskapuuta vai raaka-ainetta: Laskelmien ja luokittelujen metsäpolitiikka, in: M. Alastalo, M. Åkerman (Eds.), Tieto Hallinnassa Tietokäytännöt Suom, Yhteiskunnassa, Vastapaino, 2011, pp. 199–220.
[98] L. Ahlvik, S. Alhola, T. Blauberg, H. Laasonen, M. Liski, O. Malinen, et al.. Sähkön hinnannousun ja sähkötukien arvioidut vaikutukset kotitalouksiin, Valtion Taloudellinen Tutkimuskeskus VATT Institute for Economic Research, Helsinki, Finland, 2023. https://datahuonepilotti.fi/wp-content/uploads/2023/02/datahuone-raportti-1-2023-sahkon-hinnannousun-ja-sahkotukien-arvioidut-vaikutukset-kotitalouksiin-paivitetty-20230215.pdf.
[99] VATT, Datahuone: Suurituloisimmat kotitaloudet käyttävät moninkertaisesti enemmän sähköä kuin pienituloiset. https://vatt.fi/-/datahuone-suurituloisimmat-kotitaloudet-kayttavat-moninkertaisesti-enemman-sahkoa-kuin-pienituloiset, 2022. (Accessed 11 January 2023).
[100] H. Savikko, V.-P. Hokkanen, M. Alkula, H. Rautiainen, H. Koutonen, Tuulivoiman Aluetalousvaikutukset. Työllisyysluvut J Aluetalousvaikutukset Eri Elinkaaren Vaiheissa, Suomen Tuulivoimayhdistys ry and Ramboll oy, 2019. https://www.tuulivoimayhdistys.fi/media/tuulivoiman-aluetalousvaikutukset-29.4.2019.pdf.
[101] Energiateollisuus ry (Finnish Energy), Kaukolämmön hintatilasto (Price statistics for district heating). https://energia.fi/tilastot/kaukolammon-hintatilasto/, 2024. (Accessed 15 April 2024).
[102] T.L. Bredvold, T.H.J. Inderberg, Shockingly cold and electricity-dependent in a rich context: energy poor households in Norway, Energy Res. Social Sci. 91 (2022) 102745, https://doi.org/10.1016/j.erss.2022.102745.