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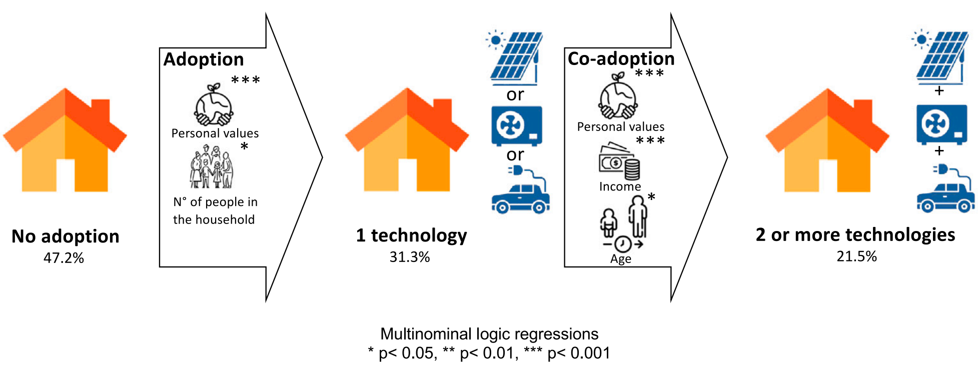

Maria Lagomarsino, Mart van der Kam, Zahra Rahmani Azad, David Parra, Ulf J.J. Hahnel

maria.lagomarsino@unige.ch (M.L.)
ulf.hahnel@unibas.ch (U.J.J.H.)

Highlights

21.5% of the sample are *co-adopters*

Adoption and co-adoption decisions are influenced differently by key determinants

Co-adoption primarily occurs in close temporal proximity

Evidence for negative impacts of technology adoption on subsequent adoption

Lagomarsino et al., iScience *26*, 107815
October 20, 2023
https://doi.org/10.1016/j.isci.2023.107815

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Co-adoption pathways toward a low-carbon energy system

Maria Lagomarsino,[1,2,*] Mart van der Kam,[1,3] Zahra Rahmani Azad,[1] David Parra,[3,4] and Ulf J.J. Hahnel[1,2,5,*]

SUMMARY

Low-carbon technology adoption is an essential element of energy transitions toward net-zero emissions around the world. To exploit the full potential of low-carbon technologies, households should ideally co-adopt multiple low-carbon technologies. Whereas previous research primarily investigated predictors of single-technology adoption in isolation, here we focus on the co-adoption of multiple low-carbon technologies, including solar photovoltaics, stationary batteries, heat pumps, and electric vehicles, to examine the interconnections between adoption decisions and the potential of certain technologies to serve as "entry points" for the co-adoption of multiple low-carbon technologies. Based on a sample of 1967 homeowners, we identified unique demographic and psychological variables associated with co-adoption. We moreover observed specific co-adoption patterns across time in that the adoption of one technology increased the likelihood of adopting another technology. This effect, however, was primarily driven by co-adoption in close temporal proximity, pointing to opportunities for targeted policies that support technology bundles.

INTRODUCTION

Many countries worldwide have pledged to meet net-zero emissions targets by 2050 with the vital objective of limiting the rise in global temperatures as soon as possible.[1,2] The energy sector is the primary global source of greenhouse gas (GHG) emissions (73.2% of total emissions), with *transportation* and *energy use in buildings* accounting for 16.2% and 17.5% of total emissions, respectively.[3] In order to achieve net-zero targets, solutions on both the supply side and the demand side should be mobilized,[4] as well as storage and flexible demand solutions. That is, national energy strategies should aim to replace fossil-based technologies with low-carbon alternatives, and substantially increase the share of renewable energy supported by enhanced forms of storage.

Households are key to achieving these objectives. Households can adopt low-carbon technologies that replace carbon-based fuels with electricity, such as heat pumps and electric vehicles (EVs) as well as renewable energy technologies that produce electricity, such as photovoltaic (PV) solar systems. Additionally, stationary batteries can help maintain grid stability and provide economic advantages in the long run, as feed-in tariffs are often lower than purchase tariffs. When these technologies are combined (co-adopted) at the household level, the locally produced electricity can be directly used to cover the electricity demand of heat pumps and EVs. Although researchers, governments, and policymakers have made strong efforts to study how to accelerate the adoption of single low-carbon technologies,[5] little attention has been drawn to the impact of the adoption of one low-carbon technology on the adoption of others.

Unveiling possible dependencies or barriers among the adoption of different technologies from a consumer perspective (*co-adoption pathways*) can provide important insights to accelerate the diffusion of low-carbon technologies, which is still far from envisaged targets.[2,6,7] Systematic research from the behavioral and social sciences is needed to increase the understanding of consumer decision-making in the context of co-adoption of low-carbon technologies. This research area bears the potential to foster the development of evidence-based policies to eventually increase the uptake of multiple low-carbon technologies.

The importance of co-adoption for reaching net-zero targets is supported by technical research.[1,6] On the demand side, low-carbon technologies are more efficient than conventional ones and therefore allow for a reduction in energy consumption. However, the envisaged emission reduction is possible only if the increased demand resulting from electrification is covered by an equivalent or even heightened production of electricity from renewable sources. While the emission reduction potential of technologies such as EVs is high, global EVs' life cycle GHG emissions are currently only 20%–30% lower compared to the emissions from conventional internal combustion engine (ICE) vehicles.[8] This low percentage is explained by the emissions associated with battery manufacturing and the still high share of fossil energy sources in the energy mix used to power EVs in many countries.[9–11] Although technical innovations in the manufacturing phase of batteries are discussed,[12]

[1]Psychology of Sustainability and Behavior Change, Faculty of Psychology, University of Basel, Missionsstasse 62a, 4055, Basel, Switzerland
[2]Swiss Center for Affective Sciences, University of Geneva, Chemin des Mines 9, 1202 Geneva, Switzerland
[3]Energy Efficiency Group of the Institute of Environmental Sciences, University of Geneva, Bd Carl Vogt 661205, Geneva, Switzerland
[4]Hydrogen and Power-to-X Department, Iberian Centre for Research in Energy Storage, Polígono 13, Parcela 31, "El Cuartillo", 10004 Cáceres, Spain
[5]Lead contact
*Correspondence: maria.lagomarsino@unige.ch (M.L.), ulf.hahnel@unibas.ch (U.J.J.H.)
https://doi.org/10.1016/j.isci.2023.107815

the most promising additional cuts in emissions are projected in the use phase of EVs by increasing the share of renewables in the energy mix.[13] For example, full-battery EV charging powered by 100% renewable energy can lead to 78%–81% lower life cycle GHG emissions than ICE vehicles in Europe.[14]

Similarly, electric heat pumps are significantly more efficient than natural gas boilers, up to three times more, which make them a more sustainable option to heat and cool indoor spaces.[15–17] This enhanced efficiency translates into substantial reductions in emissions, i.e., 35% less life cycle emissions than fossil boilers on a global average.[18] However, without co-adopting PV solar systems, the use of heat pumps relies on the available electricity supply mix, which can significantly decrease the environmental benefits. Similar to EVs, the increase of renewable energy supply can greatly help maximizing the emission reduction benefits of heat pumps.[18] For example, scenario-based results in the UK suggest that with an 85% renewable energy mix, heat pumps reduce lifetime GHG emissions by 78% compared to gas boilers.[19]

Turning to the supply side, renewable energy sources such as solar and wind are intrinsically intermittent. For example, solar energy production fluctuates greatly across the day and seasons, which translates in high imbalances between PV electricity supply and household demand at both temporal scales.[20] This imbalance results in low rates of produced solar energy that is consumed directly, referred as self-consumption. In Europe, for instance, average household self-consumption rates range between 25% and 45% only.[21,22] The variable production of solar energy also challenges the stability of the grid, in particular at the distribution level.[23,24] Thus strategies to increase self-consumption are investigated, supported, and encouraged by researchers and policymakers alike.[25,26]

Stationary batteries are emerging as a key option to increase self-consumption and improve the utility of PV solar systems (e.g., by load leveling and voltage regulation).[27,28] Yet, other options exist. For example, EVs and heat pumps also increase significantly the self-consumption rate of PV solar systems, reducing overall costs for consumers and contributing to offset the household carbon footprint.[29,30] Scenario-based studies estimate self-consumption to attain levels between 70% and 100% when various low-carbon technologies are coupled with a PV solar system.[31–34] Moreover, recent studies indicated that households that co-adopted multiple low-carbon technologies are likely to change their electricity consumption patterns, resulting in reduced net load.[35–37]

Taken together, the technical literature underlines the importance of coupling low-carbon technologies with solar renewable electricity, thus emphasizing the high complementarity benefits among EVs, batteries, heat pumps, and PV solar systems. The benefits of increasing PV self-consumption through co-adoption of additional low-carbon technologies will become more important with higher share of PV solar systems: the more households adopt PV solar systems, the less PV energy surplus can be absorbed by other loads in the neighborhood. The resulting voltage rise and increased power flow put pressure on low-voltage grids and limits the number of PV solar systems that can be integrated.[38] Increasing PV self-consumption by aligning electricity demand with PV energy production at the household level can significantly alleviate these pressures.[39] Household co-adoption of low-carbon technologies may thus play a key role in achieving net-zero targets. Whereas the benefits of co-adoption are evident from a technical perspective, little is known about consumer decision-making with regard to low-carbon technology co-adoption. This is an important research gap as consumer investment decisions hold a pivotal role in the diffusion and co-diffusion of low-carbon technologies.

Past research in the social sciences has mainly looked at the diffusion of singles technologies and the determinants of their adoption, highlighting the relevance of demographic, situational, and contextual factors,[40–43] as well as of psychological characteristics, such as personal motivation.[41,44] Among the demographic variables, age, income, and home ownership have been shown to be important predictors of low-carbon technology adoption.[40,41]

Individual variables, such as having a sustainable lifestyle and knowledge of the energy system, have also been found to influence adoption decisions.[45] Brown and colleagues[45] further found that technology-specific factors can make adoption less attractive, including characteristics of low-carbon technologies, such as low mileage of EVs, or existing preconditions such as the installation of a gas-based heating system for the adoption of heat pumps. An additional contextual factor is peer behavior, which has been shown to influence household investments in low-carbon technologies in a direct (i.e., word-of-mouth) and indirect (i.e., spatial peer effects) manner.[46]

Regarding psychological characteristics, Korcaj and colleagues[43] observed that perceived individual benefits such as status and financial benefits were strongly associated with PV solar system adoption intentions, whereas perceived collective benefits such as environmental benefits seemed to be of less relevance for such adoption decisions. In contrast, Herberz and colleagues[47] observed that perceived environmental motives were the strongest predictor of EV adoption intentions, whereas financial and status aspects were less relevant.

Findings from previous literature provide straightforward implications for the design of policies to promote the uptake of single technologies, but do not account for potential interactions between adoption decisions and thus might be less suitable for the design of policies to motivate co-adoption of low-carbon technologies. Here, we broaden the scope of adoption research by examining the co-adoption of low-carbon technologies, including the analysis of the demographic and psychological determinants of co-adoption choices as well as the impact of the adoption of one technology on subsequent adoption choices (sequential *co-adoption pathways*). With respect to psychological factors, we assessed to what extent our respondents felt the need to contribute to the Swiss energy transition, so to account for their values and personal motivation in this context.

We expected that—overall—the adoption of one low-carbon technology is associated with future purchases of additional low-carbon technologies, with specific pairs of technologies to have a more pronounced association (e.g., PV solar system and heat pump co-adoption). Based on literature from psychology and behavioral economics, we hypothesized an association between adoption decisions across technologies. Research on behavioral consistency, for instance, predicts that humans strive to be consistent in their behavior across situations.[48–50] In accordance with this literature, positive environmental actions such as the adoption of low-carbon technologies can increase a person's environmental self-identity, which in turn increases the likelihood of future pro-environmental decisions.[51,52]

Mental accounting theory may further explain the cognitive mechanisms underlying co-adoption and especially the simultaneous purchase of technologies.[53,54] The hedonic editing principle from the mental accounting literature proposes that consumers tend to take more risk when losses are aggregated, in other words when losses are perceived as a single unit (e.g., installing a heat pump and a solar system as part of a house-renovation plan) rather than as recurring events (e.g., considering separate offers for a solar system and a heat pump at different time points).[54,55] This is in line with predictions from prospect theory and more specifically the assumed convex value function for losses, which implies that multiple small losses are perceived as more negative than one large loss.[56,57]

Moreover, an emerging stream of research highlights consumers' appreciation of bundling PV solar systems with other low-carbon technologies.[25,58,59] Marketing literature suggests that consumers positively evaluate bundles of complementary products because bundles reduce search costs.[60–62] For example, vacation travel packages are often preferred over individual bookings of the hotels and train tickets as the former reduces cognitive costs for planning. The added value associated with bundling is higher for unfamiliar, risky, or expensive products.[63] These findings indicate that co-adoption is more likely to take place in close proximity in time, especially in the context of new and unfamiliar technologies such as low-carbon technologies.[64,65]

Based on our analysis of the literature, we formulate the following research questions: (i) What are the demographic and psychological determinants of co-adoption decisions and how do they differ from single-technology adoption decisions? (ii) What are prominent sequential *co-adoption pathways* of low-carbon technologies? (iii) To what extent does the adoption of one technology stimulate or hinder the adoption of another technology (immediate or lagged), i.e., can specific co-adoption pairs of low-carbon technologies be identified? To answer these research questions, we invited all registered owners of detached and semi-detached houses in the Canton of Geneva, Switzerland, to take part in our study (see procedure for more details), resulting in a final sample of 1967 respondents (10% response rate).

We exclusively targeted homeowners because they are more likely than tenants to co-adopt PV solar systems with other low-carbon technologies such as heat pumps, as currently almost no solutions are available for tenants to install these systems on rented dwellings. Adoption data show that Switzerland is representative of the European population in terms of low-carbon technology average adoption rates.[66,67] Although our sample of homeowners in the Geneva region is characterized by higher economic wealth than the population average,[68] our research approach allows to examine a sample where substantial co-adoption of low-carbon technologies already occurred and thus provides important data on existing co-adoption patterns. By investigating villa owners in a wealthy country, our research moreover addresses recent claims on the need to focus more strongly on the role of people with high socioeconomic status in GHG reduction strategies.[69]

RESULTS

Low-carbon technology adoption

In our sample, 52.77% of respondents owned at least one low-carbon technology (i.e., heat pump, PV system, hybrid (HEV) or EV, and stationary battery), of which 40.75% had more than one technology (21.50% of the whole sample; i.e., n = 423 *co-adopters*) (see Table S1 supplementary material for more information). The most popular technology was PV solar systems (43.79% of the technologies owned), followed by heat pumps (32.46% of the technologies owned). Among mobility-related low-carbon technologies, HEVs were adopted more often than EVs (14.34% and 6.15%, respectively). Just a small percentage of respondents owned a stationary battery (3.27%), as shown in Figure 1A.

Moreover, Figure 1B shows an accelerating diffusion of all technologies in the past 20 years with PV solar system and heat pump uptake intensifying after 2014–2015, which can be attributed to increasing governmental interest in PVs and heat pumps diffusion (for example, the new energy plan implemented in the study region[70,71]). Although the stationary battery market is still at an early stage, we could observe a significant uptake in 2017. In line with cantonal subsidies and increasing market availability,[72] adoption of HEVs and EVs substantially increased over the past 20 years, especially since 2018.

Adoption and co-adoption determinants

Next, we analyzed how demographics and psychological variables were associated with the adoption (i.e., one low-carbon technology) and co-adoption (i.e., two or more low-carbon technologies) of low-carbon technologies (see STAR Methods: statistical analyses for more details). We found that both demographic and psychological factors influence adoption and co-adoption of low-carbon technologies. Specifically, the multinominal logistic model revealed a statistically significant effect of personal contribution, i.e., the extent to which a given participant felt personally obliged to contribute to the Swiss energy transition ($\chi 2(2) = 144.73$, $p < 0.001$), number of people in the household ($\chi 2(2) = 12.09$, $p = 0.002$), income ($\chi 2(4) = 15.88$, $p = 0.003$), and age ($\chi 2(2) = 9.37$, $p = 0.009$) on adoption and co-adoption, but not of education. Moreover, when added to the model, neither education, gender, nor political orientation impacted adoption and co-adoption decisions (see supplementary material, Tables S2 and S3: Model 2 & 3 for complete statistics).

As illustrated in Figure 2A, comparing the likelihood of not adopting any technology with those of adopting of one technology and co-adopting multiple technologies, respectively, showed a significant association between personal contribution and both *adoption* (see supplementary material, Table S1. Model 1: OR = 1.32, *95% CI* [1.22, 1.43], $p < 0.001$) and *co-adoption* (OR = 1.79, *95% CI* [1.60, 2.00], $p < 0.001$). The more respondents felt a sense of personal obligation to contribute to the Swiss energy transition, the more they adopted and, especially, co-adopted low-carbon technologies. Comparing the likelihood to adopt vs. the likelihood to co-adopt, the impact of personal contribution was stronger for co-adoption compared to adoption (see supplementary material, Table S3. Model 1: OR = 1.36, 95% CI [1.21, 1.52], $p < 0.001$).

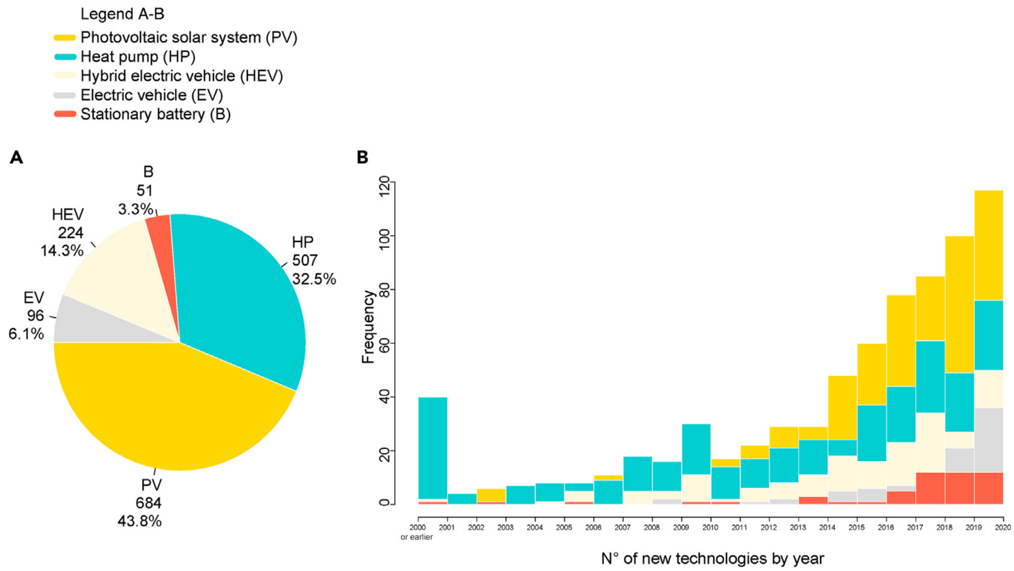

Figure 1. Low-carbon technology adoption in the sample (N = 1967)

(A) Amount of the low-carbon technologies adopted in the sample.

(B) Adoption of low-carbon technologies across time in the sample.

Note: Photovoltaic solar system (PV), heat pump (HP), hybrid (HEV) and electric (EV) vehicle, and stationary battery (B).

The results moreover showed a significant association between the number of people in the household and *co-adoption* (OR = 1.26, *95% CI* [1.10, 1.45], p = 0.001), but only a marginally significant association for *adoption* (OR = 1.14, *95% CI* [1.01, 1.28], p = 0.028). The higher the number of people in the household was, the higher was the likelihood that the respective household co-adopted multiple low-carbon technologies (see Figure 2B). However, the association between the number of people in the household and co-adoption was not statistically significant when contrasted with adoption (see supplementary material, Table S3. Model 1: OR = 1.10, 95% CI [0.96, 1.27], p = 0.168).

The results further showed a significant association between income and *co-adoption* (OR$_{[1,0,000]}$ = 1.51, *95% CI* [1.11, 2.07], p = 0.011; OR$_{\text{Income [28,001 or more]}}$ = 2.07, *95% CI* [1.32, 3.26], p = 0.002) but not with adoption (OR$_{\text{Income [13,001-28,000]}}$ = 1.10, *95% CI* [0.84, 1.45], p = 0.479; OR$_{\text{[1,001 or more]}}$ = 0.93, *95% CI* [0.59, 1.46], p = 0.748). The higher the monthly household income was, the higher was the likelihood that the respective household co-adopted multiple low-carbon technologies (see Figure 2C). When contrasted with adoption, the likelihood to co-adopt was significantly higher for the highest income segment compared to the lowest income segment (see supplementary material, Table S3. Model 1: OR$_{\text{Income [28,001 or more]}}$ = 2.23, *95% CI* [1.39, 3.61], p = 0.001).

Finally, there was an association between age and *co-adoption* (OR = 1.02, *95% CI* [1.01, 1.04], p = 0.002) but not with *adoption* (OR = 1.01, *95% CI* [0.99, 1.02], p = 0.322), reflecting the circumstance that the likelihood to have multiple technologies increases with age. The association between age and *co-adoption* was marginally significant when contrasted with adoption (see supplementary material, Table S3. Model 1: OR = 1.02, 95% CI [1.01, 1.03], p = 0.034).

Technology-specific co-adoption determinants

Next, we analyzed sequential co-adoption pathways in the sample. Furthermore, we used event-history analyses to test whether the adoption of a given low-carbon technology had a statistically significant impact on the adoption of other low-carbon technologies across time.[73] To test whether potential co-adoption effects were driven by co-adoption of technologies within close temporal proximity (i.e., within the same year), we conducted additional event-history analyses in which we focused on temporally distant co-adoption only (i.e., at least a one-year lag between the adoption of both technologies) and thus isolated effects of immediate co-adoption (i.e., co-adoption within one year). In the event-history analyses, we focused on the combination of PV systems with other low-carbon technologies, namely heat pumps, EVs and HEVs, and stationary batteries. The rationale was that these technology combinations cover both, the supply and demand side at the household level. We compared these results on actual co-adoption patterns with subjective reports of technology adopters in the sample. Specifically, we assessed how the actual adoption of a given technology increased their interest in the adoption of other low-carbon technologies.

Figure 3 provides an illustration of co-adoption pathways of low-carbon technologies in our sample (n = 423 *co-adopters*, not visualizing the 929 respondents that had no technologies and the 615 who had just one technology). The Sankey graph depicts the order in which respondents adopted the low-carbon technologies of interest. PV systems (24.59%) and heat pump (26.95%) were mostly frequently adopted as first, stand-alone, technologies or within the same year (21.75%).

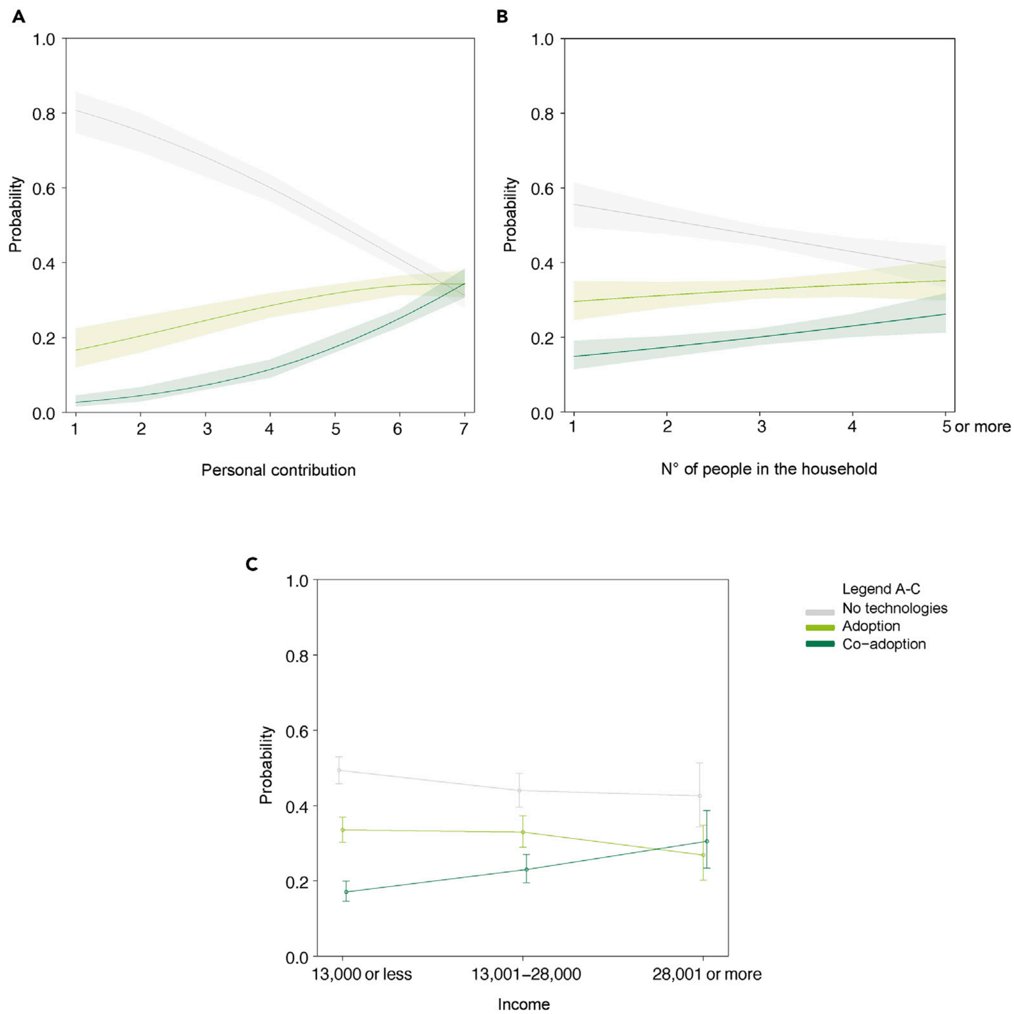

Figure 2. Visualization of the variables associated with the likelihood to adopt and co-adopt low-carbon technologies

(A–C) Likelihood to have no low-carbon technology, adopt one technology, and co-adopt multiple technologies as a function of a) perceived obligation to contribute to the Swiss energy transition, b) number of individuals in the household, and c) household income in Swiss francs. Note: *Personal contribution*: "I feel a personal obligation to contribute to the Swiss energy transition" (7-point Likert scale: 1 = *Strongly disagree*, 7 = Strongly agree).

Co-adoption effects of PV systems and heat pumps

The event-history analyses showed that the adoption of heat pumps significantly increased the likelihood to adopt PV systems and vice versa ($\chi^2(1) = 46.72$, $p < 0.001$ and $\chi^2(1) = 9.45$, $p = 0.002$, respectively). As illustrated in Figure 4A, the cumulative likelihood to adopt a PV system across the time period of interest (2000 until 2020) was higher in the group of participants that adopted a heat pump before PV adoption or in the same year. These effects can be observed especially from 2016 with increasing differences between groups from this time point. However, when excluding co-adoption of the two technologies within the same year (i.e., bundling effects), no effect of previous heat pump adoption on PV adoption could be observed ($\chi^2(1) = 0.59$, $p = 0.442$, see Figure 4B). For heat pump adoption, the event-history analysis excluding co-adoption within the same year even revealed negative co-adoption effects in that the likelihood to adopt a heat pump was smaller in the group of respondents that previously adopted a PV system ($\chi^2(1) = 24.25$, $p < 0.001$, see supplementary material Figure S1 for visualization, and Table S4 for complete results). Taken together, co-adoption of PV systems and heat pumps mostly occurred within the same year with elevated frequencies in the recent years (see Figure 4C). When isolating effects of bundled co-adoption, previous adoption of one technology had no or even negative effects on the adoption of other technologies.

Participants' subjective reports corroborated actual co-adoption findings to a large extent: participants reported that the adoption of a PV system influenced their interest in adopting a heat pump. Specifically, 42.80% of respondents reported that their experience with a PV system increased their interest in installing a heat pump. However, there were a significant proportion of participants who reported having a lower interest in adopting a heat pump after the purchase of a PV solar system. In line with the findings on actual adoption, this effect was stronger than the other way around in that 26.65% of respondents reported that the adoption of a PV system made them less or much less interested in

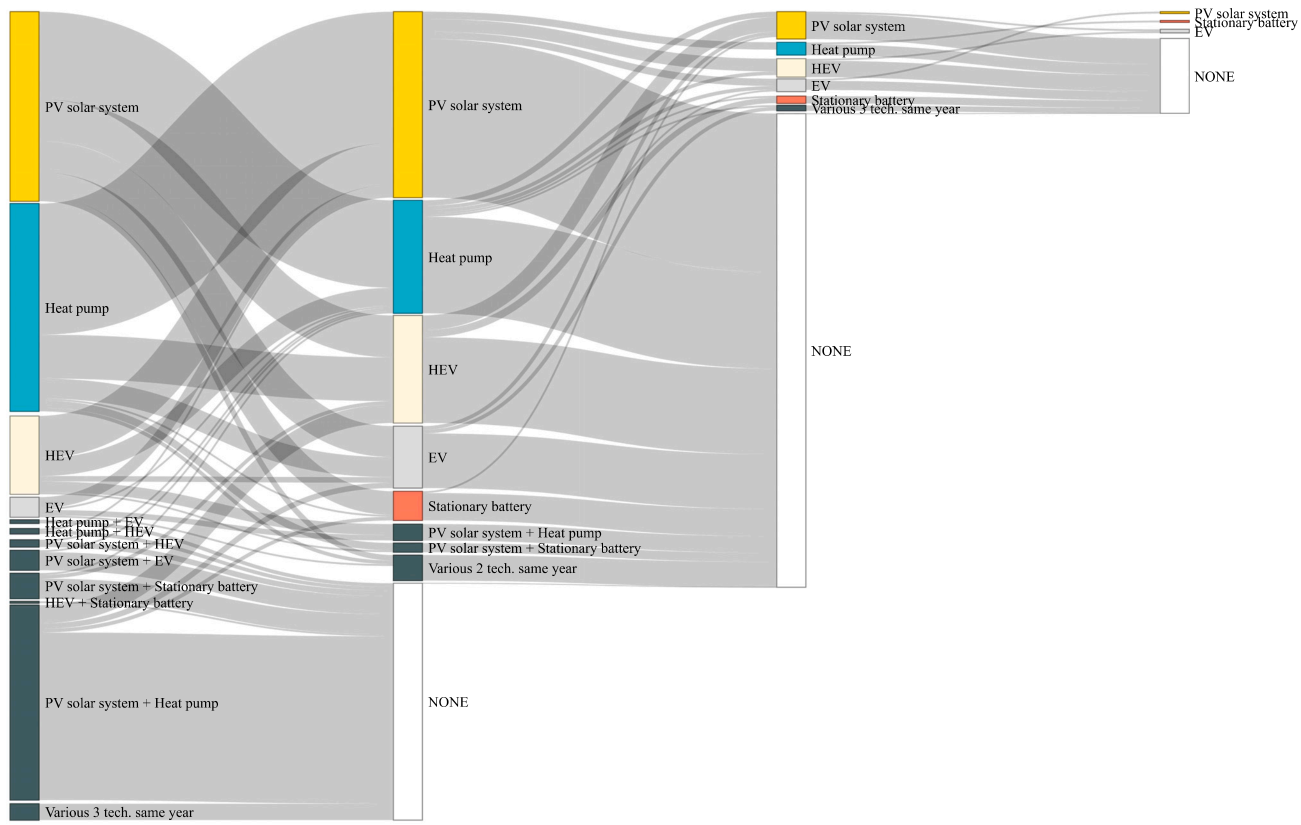

Figure 3. Co-adoption pathways of low-carbon technologies in the sample (n = 423 co-adopters)

The graph represents the subset of participants that co-adopted low-carbon technologies. The first technology adoption is presented on the very left side of the figure and, moving to the right, the graph represents the co-adoption flow until the last purchased technology. The size of the vertical bars reflects the absolute numbers of co-adopters for a given technology. Percentage values are not presented to retain clarity. Sample size specification for the first technology groups: PV solar system (n = 104); Heat pump (n = 115); HEV (n = 41); EV (n = 11); Heat pump +EV (n = 2); Heat pump +HEV (n = 3); PV solar system +HEV (n = 4); PV solar system + EV (n = 11); PV solar system + Stationary battery (n = 14); HEV + Stationary battery (n = 1); PV solar system + Heat pump (n = 108); Various 3 technology in the same year (n = 9).

adopting a heat pump, whereas 19.95% reported a similar decline in interest in PV adoption after the purchase of a heat pump (see Figures 5A and 5B).

Co-adoption effects of PV systems and HEVs and EVs

The event-history analyses showed that the adoption of EVs did not significantly increase the likelihood to adopt PV systems ($\chi^2(1) = 2.35$, $p = 0.125$). However, adopting a PV system before or in the same year significantly increased the likelihood to adopt an EV ($\chi^2(1) = 6.23$, $p = 0.013$). This effect, however, diminished when excluding co-adoption of the two technologies within the same year ($\chi^2(1) = 0.02$, $p = 0.900$). Taken together, only co-adoption effects of PV systems on EVs can be observed that were exclusively driven by co-adoption within the same year (see supplementary material, Figures S2 and S3 for visualization; Table S5 for complete results).

While no effects of actual EV adoption on PV adoption can be observed, subjective reports showed that the adoption of EVs substantially increased interest in PV solar systems (for 77.62% respondents indicated that the purchase of an EV made them more or much more interested in PV systems; see Figure 5A). Given the relatively low actual adoption rate of EVs in our sample (6.15%) in which most EV purchases took place in the very recent years, the subjective reports might thus point to co-adoption effects in the future when elevated interest in PV systems after EV purchases is translated into actual co-adoption behavior.

In line with findings on EVs, the adoption of a HEV did not increase the likelihood to adopt a PV system ($\chi^2(1) = 2.17$, $p = 0.141$). However, a negative co-adoption effect emerged when excluding bundling effects (i.e., co-adoption in the same year) in that the adoption of an HEV decreased the likelihood to adopt a PV system ($\chi^2(1) = 4.68$, $p = 0.031$). Focusing on HEV adoption, we observed a negative co-adoption effect of PV systems on HEVs in that the likelihood to adopt a HEV was smaller in the group of participants who adopted a PV system compared to those who did not adopt this technology ($\chi^2(1) = 7.72$, $p = 0.005$). This pattern remained when excluding co-adoption effects within the same year ($\chi^2(1) = 12.51$, $p < 0.001$; see supplementary material, Figures S4 for visualization and Table S6 for complete results).

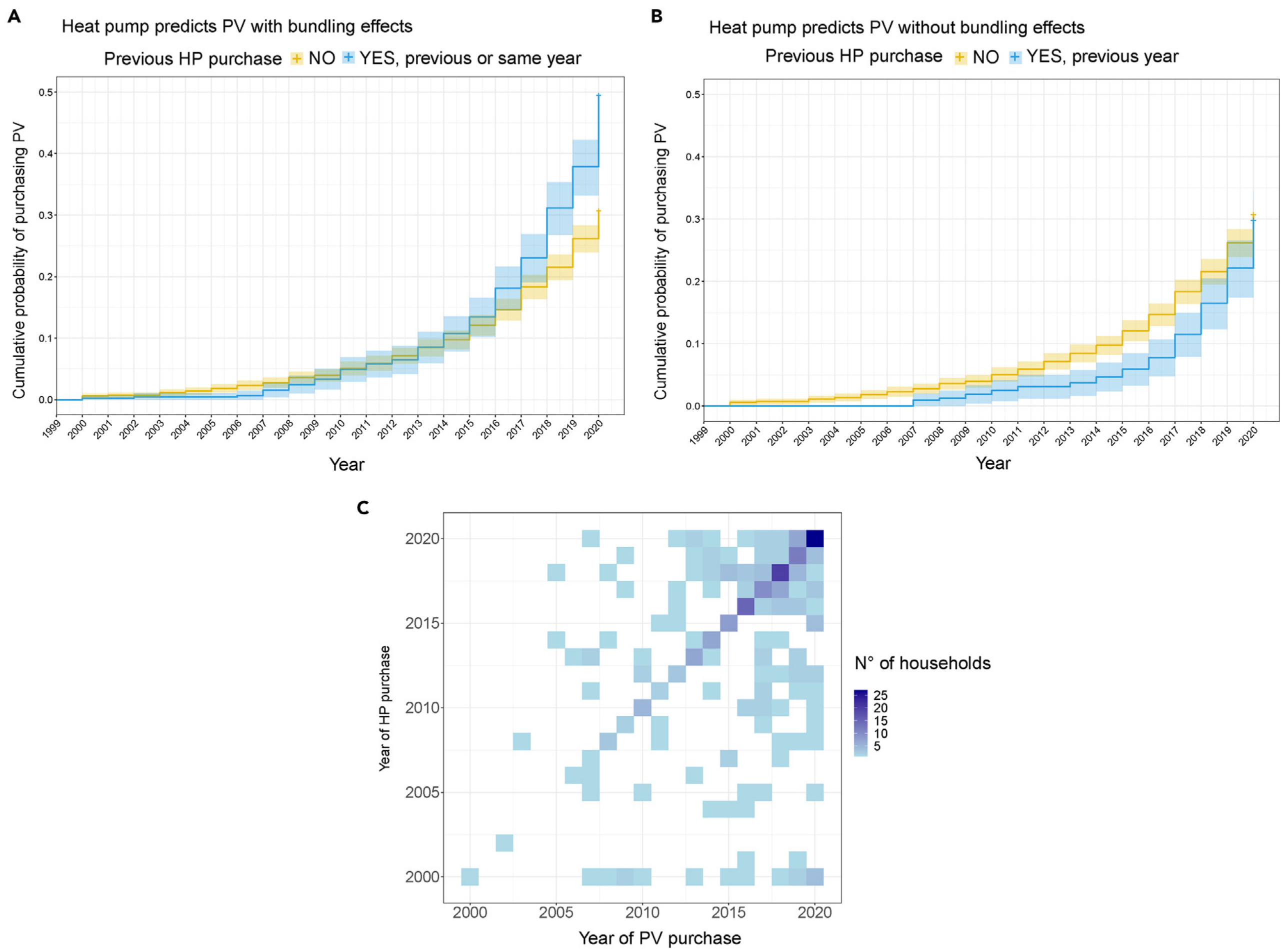

Figure 4. Impact of heat pump adoption on the likelihood to adopt PV systems across time

(A) Heat pumps were adopted in the same year or the years before PV adoption.

(B) Heat pumps were only adopted in the years before PV adoption, excluding co-adoption within the same year.

(C) Temporal occurrence of PV and heat pump adoption. The diagonal indicates co-adoption within the same year. Values below the diagonal indicate that a heat pump was adopted before a PV system whereas values above the diagonal indicate that a PV system was adopted before a heat pump.

Findings on subjective reports were largely in line with actual co-adoption patterns. Albeit overall high, the reported interest in adopting a PV system after the adoption of a HEV was smaller compared to prior EV adoption (49.72% for HEVs compared to 77.62% for EVs, see Figure 5A). Turning to the effects of PV system adoption on HEV adoption, subjective reports showed that 38.29% of respondents reported to be less or much less interested in adopting a HEV after the adoption of a PV system (see Figure 5D).

Co-adoption effects of PV and stationary batteries

As illustrated in Figure 3, stationary batteries were mostly adopted after the adoption of PV systems or in combination but not before PV adoption. We were interested in the extent to which these co-adoption effects can be exclusively explained by bundling of PV and batteries within the same year. As illustrated in Supplementary Material, Figure S5, event-history analysis showed that the likelihood to adopt a battery was significantly higher in the group of PV adopters including and excluding bundling effects (including bundling: $\chi^2(1) = 57.00$, excluding bundling: $p < 0.001$; $\chi^2(1) = 16.18$, $p < 0.001$; Table S7 for complete results). This finding has been supported by subjective reports showing that 38.71% of respondents reported that their experience with a PV system increased their interest to install a stationary battery (see Figure 5C).

DISCUSSION

Co-adoption of low-carbon technologies by households is an important component of energy transitions around the world, as co-adoption enables the direct use of solar electricity for heating and mobility.[14,19] Therefore, it helps to decarbonize both residential heating and the

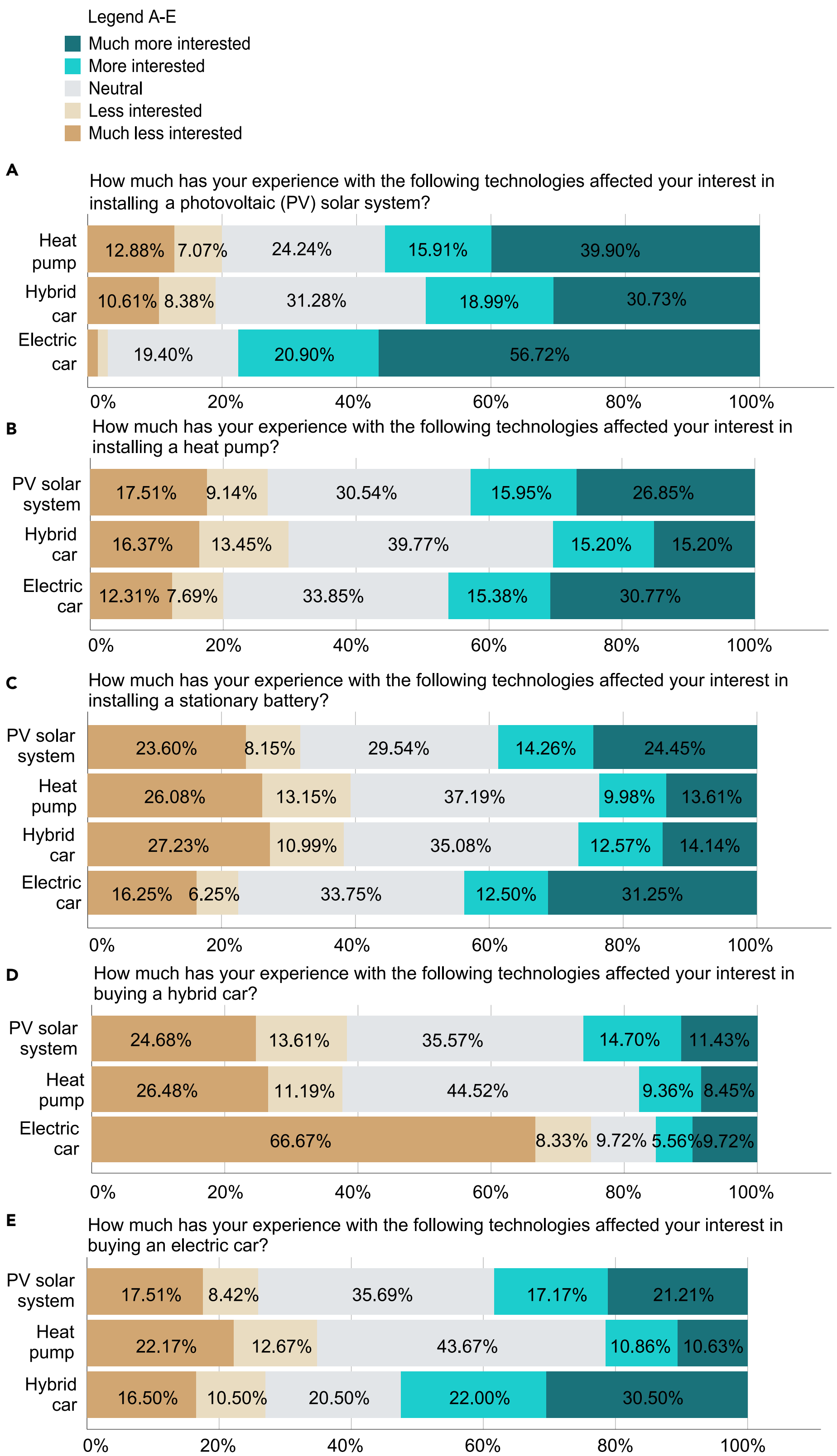
Legend A-E
Much more interested
More interested
Neutral
Less interested
Much less interested
A
How much has your experience with the following technologies affected your interest in installing a photovoltaic (PV) solar system?
Heat pump
12.88%
7.07%
24.24%
15.91%
39.90%
Hybrid car
10.61%
8.38%
31.28%
18.99%
30.73%
Electric car
19.40%
20.90%
56.72%
0%
20%
40%
60%
80%
100%
B
How much has your experience with the following technologies affected your interest in installing a heat pump?
PV solar system
17.51%
9.14%
30.54%
15.95%
26.85%
Hybrid car
16.37%
13.45%
39.77%
15.20%
15.20%
Electric car
12.31%
7.69%
33.85%
15.38%
30.77%
0%
20%
40%
60%
80%
100%
C
How much has your experience with the following technologies affected your interest in installing a stationary battery?
PV solar system
23.60%
8.15%
29.54%
14.26%
24.45%
Heat pump
26.08%
13.15%
37.19%
9.98%
13.61%
Hybrid car
27.23%
10.99%
35.08%
12.57%
14.14%
Electric car
16.25%
6.25%
33.75%
12.50%
31.25%
0%
20%
40%
60%
80%
100%
D
How much has your experience with the following technologies affected your interest in buying a hybrid car?
PV solar system
24.68%
13.61%
35.57%
14.70%
11.43%
Heat pump
26.48%
11.19%
44.52%
9.36%
8.45%
Electric car
66.67%
8.33%
9.72%
5.56%
9.72%
0%
20%
40%
60%
80%
100%
E
How much has your experience with the following technologies affected your interest in buying an electric car?
PV solar system
17.51%
8.42%
35.69%
17.17%
21.21%
Heat pump
22.17%
12.67%
43.67%
10.86%
10.63%
Hybrid car
16.50%
10.50%
20.50%
22.00%
30.50%
0%
20%
40%
60%
80%
100%

Figure 5. Self-reported change in interest to adopt a PV system, heat pump, battery, HEV, and EV after the adoption of another low-carbon technology

(A) The influence of other low-carbon technologies on the interest to install a PV solar system. $N_{heat\ pump} = 396$; $n_{hybrid\ car} = 179$; $n_{electric\ car} = 67$. We excluded responses for stationary battery due to small sample size ($n_{stationary\ battery} = 27$).

(B) The influence of other low-carbon technologies on the interest to install a heat pump. $N_{solar\ system} = 514$; $n_{hybrid\ car} = 171$; $n_{electric\ car} = 65$. We excluded responses for stationary battery due to small sample size ($n_{stationary\ battery} = 37$).

(C) The influence of other low-carbon technologies on the interest to install a stationary battery. $N_{solar\ system} = 589$; $n_{heat\ pump} = 441$; $n_{hybrid\ car} = 191$; $n_{electric\ car} = 80$.

(D) The influence of other technologies on the interest to install a hybrid vehicle. $N_{solar\ system} = 551$; $n_{heat\ pump} = 438$; $n_{electric\ car} = 72$. We excluded responses for stationary battery due to small sample size ($n_{stationary\ battery} = 43$).

(E) The influence of other technologies on the interest to install an electric vehicle. $N_{solar\ system} = 594$; $n_{heat\ pump} = 442$; $n_{hybrid\ car} = 200$. We excluded responses for stationary battery due to small sample size ($n_{stationary\ battery} = 45$). Only adopters of low-carbon technologies were asked how their experience with their adopted technology or technologies influenced their interest in adopting other low-carbon technologies. The respondents who had more than one low-carbon technology were asked only about technologies that they adopted afterward and that have not been adopted (NA = if they installed the technology before).

transportation sector. Thus, instead of focusing on individual diffusion patterns, here we focus on the co-adoption of multiple low-carbon technologies by investigating unique determinants of co-adoption (compared to adoption), and by highlighting common co-adoption pathways. In our sample of Geneva homeowners, 31.27% of respondents had only one low-carbon technology (i.e., a heat pump, PV solar system, HEVs and EVs, and stationary battery), and 21.50% of respondents adopted multiple low-carbon technologies. We observed that both demographics and psychological variables predicted co-adoption, emphasizing the relevance of considering structural factors as well as individual values and preferences when studying technology co-diffusion. Specifically, high income, the number of people in the household, and a perceived personal obligation to contribute to the energy transition were the strongest predictors of co-adoption in our study. The association between income and personal obligation to contribute to the energy transition and co-adoption was also significantly stronger than the associations between these factors and the adoption of a single technology. These results emphasize the importance of investigating co-adoption in addition to the analysis of single-technology adoption, as the influence of core predictors differs between adoption and co-adoption decisions.

When looking at specific co-adoption pathways, we could see that a third of co-adopters installed a PV solar system and a heat pump in the same year (*immediate co-adoption*), but other combinations of PV solar systems could be observed as well. Event-history analyses showed that co-adoption within the same year was a strong determinant of co-adoption patterns. In accordance, effects of heat pump adoption on PV system adoption diminished when controlling for immediate co-adoption of the technologies. Economic incentives such as bundling product offers could partly account for this finding. Marketing literature on the effect of product bundling emphasizes further the subjective added value of installing multiple technologies at once, as doing so reduces search costs.[25,58,59] Moreover, in line with the hedonic editing principle of the mental accounting literature, accounting for a large joint investment in several technologies (one expense) is perceived as less negative than multiple reoccurring investments separately (repeated expenses), even if the actual spending is the same.[53,54] These streams of literature could explain our empirical finding that lagged co-adoption was less prevalent than bundled co-adoption of technologies in close temporal proximity.

Our results further illustrated that the adoption of one technology can influence the self-reported interest in adopting other low-carbon technologies. Specifically, adopting an EV increased interest in adopting a PV solar system even though there was no effect of actual EV adoption on PV adoption. That is, the use of electric mobility increases the interest in powering the EV with self-generated electricity, an effect which might translate into actual co-adoption behavior within the next years. Practitioners can learn from these first insights to structure policies that incentivize the adoption of different low-carbon technologies in a specific order. However, there is a consistent subset of respondents (~20%) for whom their experience with a PV system decreased their interest in adopting any of the other low-carbon technologies. These findings on self-reports are corroborated by our actual adoption data: when excluding bundling effects, the likelihood to adopt a heat pump and a HEV was significantly smaller in the group of homeowners that adopted a PV system compared to those not having adopted PV. One explanation for the observed negative impact of PV adoption on heat pumps and HEV adoption is that large investments in one technology reduce the overall household budget for subsequent large investments. In this light, it is even more interesting that this negative impact was attenuated under certain conditions, for instance when heat pumps were adopted *before* PV systems. Here, it could be speculated that the increased household electricity demand caused by heat pumps increased the motivation to meet this demand by self-generated PV electricity.

Low income is among the highest barriers to the adoption of low-emission technologies according to previous research.[64,65] In our sample of homeowners, high income was associated with a higher likelihood to co-adopt; however, co-adoption occurred at all levels of income. Especially when homeowners need to renovate their heating system or the roof of their house, low-carbon technologies may offer high advantages for a relatively small cost premium. In light of projected decreasing investment costs for most low-carbon technologies,[74–78] it is likely that the effect of income on adoption and co-adoption will decrease in the future.

We set out our study only among homeowners given that, at the time of data assessment, there were only few solutions available for tenants to install a PV solar system, stationary battery, or heat pump in their home. It would be nevertheless interesting to investigate co-adoption in the general population including tenants for two main reasons. First, it is important to understand how tenants perceive co-adoption and their intention to invest in low-carbon technologies to estimate the potential of new business models enabling tenants to invest in low-carbon technologies. Second, even when tenants do not adopt or co-adopt low-carbon technologies in their home, they may still influence the diffusion of low-carbon technologies through personal exchange with owners, which could motivate owners to install these technologies.

Supporting and facilitating co-adoption is of foremost importance when considering the current geopolitical and economic situation with rapidly increasing energy prices and limited security of supply. Taking the example of EV, single adoption of this technology is likely to become less attractive as the price to charge it is estimated to greatly increase in the years to come.[79] Co-adoption of EVs with solar systems, however, can significantly buffer the impact of price shocks. In line with previous research,[26,61] our findings show that there is potential for immediate co-adoption of EVs and PV systems, which would allow for a rapid increase in the diffusion of these key low-carbon technologies. Government and policymakers should respond to the situation and further incentivize the co-adoption of these technologies to further strengthen the EV-solar and heat pump-solar co-adoption effects observed here.

In conclusion, combinations of low-carbon technologies that produce renewable electricity and transform it into heating and mobility, such as heat pumps and EVs, are essential for the achievement of net-zero emissions objectives.[2,6,7] Here, we illustrate that the adoption of one low-carbon technology is temporally associated with the adoption of subsequent technologies, with specific technologies such as EVs that could serve as "entry points" for co-adoption of low-carbon technologies in the future. We further point to co-adoption trajectories resulted from cross-technology dependencies that can be specifically promoted by means of targeted policies. One promising option thereby is to promote co-adoption in close temporal proximity, for instance by providing subsidies for adoption of technologies pairs (PV and heat pump, PV and EVs) in bundles. We hope this research to be a starting point for systematic research addressing the co-adoption of low-carbon technologies holistically.

Limitations of the study

The empirical results reported here should be considered in the light of some limitations. Having investigated homeowners through the cooperation of the regional energy provider offered a unique and highly relevant sample, but this approach may also have increased self-selection bias. Considering how the study has been promoted, it is possible that especially those homeowners who were already interested in renewable energy participated. Moreover, our sample is representative of the population of Switzerland (e.g., gender, number of people in the house), one of the most wealthy countries in the world. Our results might thus not depict general trends at the European or worldwide level. Finally, we relied on self-reported measures which may suffer from respondents' imprecision or biases.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.107815.

ACKNOWLEDGMENTS

This research has been financially supported within two projects funded by the Swiss National Science Foundation awarded to D.P. and U.J.J.H. (Grant No. 188637) and U.J.J.H. (SNSF Eccellenza PCEFP1_203283).

AUTHOR CONTRIBUTIONS

M.L.: Conceptualization, methodology, data curation, formal analysis, investigation, writing – original draft, visualization.
M.v.d.K.: Conceptualization, methodology, writing – review & editing.
Z.R.A.: Data curation, formal analysis, visualization, writing – review & editing.
D.P.: Conceptualization, funding acquisition, writing – review & editing.
U.J.J.H.: Conceptualization, methodology, supervision, validation, funding acquisition, writing – original draft, writing – review & editing.

DECLARATION OF INTERESTS

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.

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Received: May 7, 2023
Revised: July 10, 2023
Accepted: August 30, 2023
Published: September 1, 2023

REFERENCES

1. IPCC (2019). Global warming of 1.5°C. https://doi.org/10.1017/9781009157940.001.
2. IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. https://doi.org/10.1017/9781009325844.
3. Ritchie, H. (2020). Sector by sector: where do global greenhouse gas emissions come from? - Our World in Data. https://ourworldindata.org/ghg-emissions-by-sector.
4. O'Shaughnessy, E., Shah, M., Parra, D., and Ardani, K. (2022). The demand-side resource opportunity for deep grid decarbonization. Joule *6*, 972–983. https://doi.org/10.1016/j.joule.2022.04.010.
5. IEA (2021). World Energy Outlook 2021. https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf.
6. IEA (2021). Net Zero by 2050 - A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050.
7. UN (2022). Net Zero Coalition | United Nations. https://www.un.org/en/climatechange/net-zero-coalition.
8. IEA (2021). Global EV Outlook 2021 Accelerating ambitions despite the pandemic. https://doi.org/10.1787/3a394362-en.
9. Verma, S., Dwivedi, G., and Verma, P. (2022). Life cycle assessment of electric vehicles in comparison to combustion engine vehicles: A review. Mater. Today Proc. *49*, 217–222. https://doi.org/10.1016/j.matpr.2021.01.666.
10. Xia, X., and Li, P. (2022). A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. Sci. Total Environ. *814*, 152870. https://doi.org/10.1016/J.SCITOTENV.2021.152870.
11. Tagliaferri, C., Evangelisti, S., Acconcia, F., Domenech, T., Ekins, P., Barletta, D., and Lettieri, P. (2016). Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. Chem. Eng. Res. Des. *112*, 298–309. https://doi.org/10.1016/J.CHERD.2016.07.003.
12. IEA. Innovation in batteries and electricity storage. A global analysis based on patent data. https://www.iea.org/reports/innovation-in-batteries-and-electricity-storage.
13. Andersson, Ö., and Börjesson, P. (2021). The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications. Appl. Energy *289*, 116621. https://doi.org/10.1016/J.APENERGY.2021.116621.
14. Bieker, G. (2021). A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars.
15. Tong, Y., Kozai, T., Nishioka, N., and Ohyama, K. (2010). Greenhouse heating using heat pumps with a high coefficient of performance (COP). Biosyst. Eng. *106*, 405–411. https://doi.org/10.1016/J.BIOSYSTEMSENG.2010.05.003.
16. Streicher, K.N., Padey, P., Parra, D., Bürer, M.C., and Patel, M.K. (2018). Assessment of the current thermal performance level of the Swiss residential building stock: Statistical analysis of energy performance certificates. Energy Build. *178*, 360–378. https://doi.org/10.1016/J.ENBUILD.2018.08.032.
17. Carroll, P., Chesser, M., and Lyons, P. (2020). Air Source Heat Pumps field studies: A systematic literature review. Renew. Sustain. Energy Rev. *134*, 110275. https://doi.org/10.1016/J.RSER.2020.110275.
18. Knobloch, F., Hanssen, S., Lam, A., Pollitt, H., Salas, P., Chewpreecha, U., Huijbregts, M.A.J., and Mercure, J.F. (2020). Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat. Sustain. *3*, 437–447. https://doi.org/10.1038/s41893-020-0488-7.
19. Sevindik, S., Spataru, C., Domenech Aparisi, T., and Bleischwitz, R. (2021). A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK. Energies *14*, 3027. https://doi.org/10.3390/EN14113027.
20. Parra, D., Walker, G.S., and Gillott, M. (2014). Modeling of PV generation, battery and hydrogen storage to investigate the benefits of energy storage for single dwelling. Sustain. Cities Soc. *10*, 1–10. https://doi.org/10.1016/J.SCS.2013.04.006.
21. Panos, E., and Margelou, S. (2019). Long-Term Solar Photovoltaics Penetration in Single- and Two-Family Houses in Switzerland. Energies *12*, 2460. https://doi.org/10.3390/EN12132460.
22. Quoilin, S., Kavvadias, K., Mercier, A., Pappone, I., and Zucker, A. (2016). Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. Appl. Energy *182*, 58–67. https://doi.org/10.1016/J.APENERGY.2016.08.077.
23. Gupta, R., Pena-Bello, A., Streicher, K.N., Roduner, C., Thöni, D., Thöni, D., Patel, M.K., and Parra, D. (2021). Spatial analysis of distribution grid capacity and costs to enable massive deployment of PV, electric mobility and electric heating. Appl. Energy *287*, 116504. https://doi.org/10.1016/J.APENERGY.2021.116504.
24. Sinsel, S.R., Riemke, R.L., and Hoffmann, V.H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. Renew. Energy *145*, 2271–2285. https://doi.org/10.1016/J.RENENE.2019.06.147.
25. Priessner, A., and Hampl, N. (2020). Can product bundling increase the joint adoption of electric vehicles, solar panels and battery storage? Explorative evidence from a choice-based conjoint study in Austria. Ecol. Econ. *167*, 106381. https://doi.org/10.1016/J.ECOLECON.2019.106381.
26. Kaufmann, R.K., Newberry, D., Xin, C., and Gopal, S. (2021). Feedbacks among electric vehicle adoption, charging, and the cost and installation of rooftop solar photovoltaics. Nat. Energy *6*, 143–149. https://doi.org/10.1038/s41560-020-00746-w.
27. Duhirwe, P.N., Hwang, J.K., Ngarambe, J., Kim, S., Kim, K., Song, K., and Yun, G.Y. (2021). A novel deep learning-based integrated photovoltaic, energy storage system and electric heat pump system: Optimising energy usage and costs. Int. J. Energy Res. *45*, 9306–9325. https://doi.org/10.1002/ER.6462.
28. Pena-Bello, A., Barbour, E., Gonzalez, M.C., Patel, M.K., and Parra, D. (2019). Optimized PV-coupled battery systems for combining applications: Impact of battery technology and geography. Renew. Sustain. Energy Rev. *112*, 978–990. https://doi.org/10.1016/j.rser.2019.06.003.
29. Freitas Gomes, I.S., Perez, Y., and Suomalainen, E. (2020). Coupling small batteries and PV generation: A review. Renew. Sustain. Energy Rev. *126*, 109835. https://doi.org/10.1016/J.RSER.2020.109835.
30. Pena-Bello, A., Schuetz, P., Berger, M., Worlitschek, J., Patel, M.K., and Parra, D. (2021). Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: Impacts and trade-offs for prosumers and the grid. Energy Convers. Manag. *240*, 114220. https://doi.org/10.1016/J.ENCONMAN.2021.114220.
31. Thür, A., Calabrese, T., and Streicher, W. (2018). Smart grid and PV driven ground heat pump as thermal battery in small buildings for optimized electricity consumption. Sol. Energy *174*, 273–285. https://doi.org/10.1016/j.solener.2018.08.087.
32. Rinaldi, A., Soini, M.C., Streicher, K., Patel, M.K., and Parra, D. (2021). Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation. Appl. Energy *282*, 116110. https://doi.org/10.1016/J.APENERGY.2020.116110.
33. van der Kam, M., and van Sark, W. (2015). Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study. Appl. Energy *152*, 20–30. https://doi.org/10.1016/j.apenergy.2015.04.092.
34. Litjens, G.B.M.A., Kausika, B.B., Worrell, E., and van Sark, W.G.J.H.M. (2018). A spatio-temporal city-scale assessment of residential photovoltaic power integration scenarios. Sol. Energy *174*, 1185–1197. https://doi.org/10.1016/J.SOLENER.2018.09.055.
35. Shen, X., Qiu, Y.L., Bo, X., Patwardhan, A., Hultman, N., and Dong, B. (2023). The impact of co-adopting electric vehicles, solar photovoltaics, and battery storage on

electricity consumption patterns: Empirical evidence from Arizona. Resour. Conserv. Recycl. *192*, 106914. https://doi.org/10.1016/J.RESCONREC.2023.106914.

36. Liang, J., Qiu, Y.L., Xing, B., and Xing, B. (2022). Impacts of the co-adoption of electric vehicles and solar panel systems: Empirical evidence of changes in electricity demand and consumer behaviors from household smart meter data. Energy Econ. *112*, 106170. https://doi.org/10.1016/j.eneco.2022.106170.
37. Qiu, Y.L., Xing, B., Patwardhan, A., Hultman, N., Zhang, H., and Zhang, H. (2022). Heterogeneous changes in electricity consumption patterns of residential distributed solar consumers due to battery storage adoption. iScience *25*, 104352. https://doi.org/10.1016/J.ISCI.2022.104352.
38. Bayer, B., Matschoss, P., Thomas, H., and Marian, A. (2018). The German experience with integrating photovoltaic systems into the low-voltage grids. Renew. Energy *119*, 129–141. https://doi.org/10.1016/j.renene.2017.11.045.
39. Luthander, R., Widén, J., Nilsson, D., and Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. Appl. Energy *142*, 80–94. https://doi.org/10.1016/j.apenergy.2014.12.028.
40. Singh, V., Singh, V., and Vaibhav, S. (2020). A review and simple meta-analysis of factors influencing adoption of electric vehicles. Transp. Res. Part D Transp. Environ. *86*, 102436. https://doi.org/10.1016/J.TRD.2020.102436.
41. Schulte, E., Scheller, F., Sloot, D., and Bruckner, T. (2022). A meta-analysis of residential PV adoption: the important role of perceived benefits, intentions and antecedents in solar energy acceptance. Energy Res. Soc. Sci. *84*, 102339. https://doi.org/10.1016/J.ERSS.2021.102339.
42. Sehar, F., Pipattanasomporn, M., and Rahman, S. (2017). Demand management to mitigate impacts of plug-in electric vehicle fast charge in buildings with renewables. Energy *120*, 642–651. https://doi.org/10.1016/j.energy.2016.11.118.
43. Korcaj, L., Hahnel, U.J., and Spada, H. (2015). Intentions to adopt photovoltaic systems depend on homeowners' expected personal gains and behavior of peers. Renew. Energy *75*, 407–415. https://doi.org/10.1016/J.RENENE.2014.10.007.
44. Herberz, M., Brosch, T., and Hahnel, U.J.J. (2020). Kilo what? Default units increase value sensitivity in joint evaluations of energy efficiency. Judgm. Decis. Mak. *15*, 972–988. http://journal.sjdm.org/20/200709a/jdm200709a.html.
45. Brown, M.A., Kale, S., Cha, M.K., and Chapman, O. (2023). Exploring the willingness of consumers to electrify their homes. Appl. Energy *338*, 120791. https://doi.org/10.1016/J.APENERGY.2023.120791.
46. Wolske, K.S., Gillingham, K.T., and Schultz, P.W. (2020). Peer influence on household energy behaviours. Nat. Energy *5*, 202–212. https://doi.org/10.1038/s41560-019-0541-9.
47. Herberz, M., Hahnel, U.J., and Brosch, T. (2020). The importance of consumer motives for green mobility: A multi-modal perspective. Transp. Res. Part A Policy Pract. *139*, 102–118. https://doi.org/10.1016/J.TRA.2020.06.021.
48. Funder, D.C., and Colvin, C.R. (1991). Explorations in Behavioral Consistency: Properties of Persons, Situations, and Behaviors. J. Pers. Soc. Psychol. *60*, 773–794. https://doi.org/10.1037/0022-3514.60.5.773.
49. Whitmarsh, L., and O'Neill, S. (2010). Green identity, green living? The role of pro-environmental self-identity in determining consistency across diverse pro-environmental behaviours. J. Environ. Psychol. *30*, 305–314. https://doi.org/10.1016/J.JENVP.2010.01.003.
50. Capstick, S., Whitmarsh, L., Nash, N., Haggar, P., and Lord, J. (2019). Compensatory and catalysing behavioural beliefs: Development and psychometric properties of an instrument for measuring spillover-related perceptions in seven countries. Front. Psychol. *10*, 963. https://doi.org/10.3389/FPSYG.2019.00963/XML/NLM.
51. Van Der Kam, M., Peters, A., Van Sark, W., and Alkemade, F. (2019). Agent-based modelling of charging behaviour of electric vehicle drivers. J. Artif. Soc. Soc. Simul. *22*. https://doi.org/10.18564/jasss.4133.
52. Van der Werff, E., Steg, L., and Keizer, K. (2013). The value of environmental self-identity: The relationship between biospheric values, environmental self-identity and environmental preferences, intentions and behaviour. J. Environ. Psychol. *34*, 55–63. https://doi.org/10.1016/J.JENVP.2012.12.006.
53. Hahnel, U.J.J., Chatelain, G., Conte, B., Piana, V., and Brosch, T. (2020). Mental accounting mechanisms in energy decision-making and behaviour. Nat. Energy *5*, 952–958. https://doi.org/10.1038/s41560-020-00704-6.
54. Thaler, R.H. (1985). Mental Accounting and Consumer Choice. Marketing Science *4*, 199–214. https://doi.org/10.1287/MKSC.4.3.199.
55. Thaler, R.H., and Johnson, E.J. (1990). Gambling with the House Money and Trying to Break Even: The Effects of Prior Outcomes on Risky Choice. Management Science. *36*, 643–660. https://doi.org/10.1287/MNSC.36.6.643.
56. Kahneman, D., and Tversky, A. (In Handbook of the fundamentals of financial decision making: Part I. 2013). Prospect Theory: An Analysis of Decision Under Risk. https://doi.org/10.1142/9789814417358_0006.
57. Kahneman, D., and Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. Econometrica *47*, 263–292. https://doi.org/10.2307/1914185.
58. Stauch, A. (2021). Does solar power add value to electric vehicles? An investigation of car-buyers' willingness to buy product-bundles in Germany. Energy Res. Soc. Sci. *75*, 102006. https://doi.org/10.1016/J.ERSS.2021.102006.
59. Gu, G., and Feng, T. (2020). Heterogeneous choice of home renewable energy equipment conditioning on the choice of electric vehicles. Renew. Energy *154*, 394–403. https://doi.org/10.1016/j.renene.2020.03.007.
60. Stremersch, S., and Tellis, G.J. (2018). Strategic Bundling of Products and Prices: A New Synthesis for Marketing. J. Mark. *66*, 55–72. https://doi.org/10.1509/JMKG.66.1.55.18455.
61. Plananska, J., and Gamma, K. (2022). Product bundling for accelerating electric vehicle adoption: A mixed-method empirical analysis of Swiss customers. Renew. Sustain. Energy Rev. *154*, 111760. https://doi.org/10.1016/J.RSER.2021.111760.
62. Dominique-Ferreira, S., and Antunes, C. (2020). Estimating the price range and the effect of price bundling strategies: An application to the hotel sector. Eur. J. Manag. Bus. Econ. *29*, 166–181. https://doi.org/10.1108/EJMBE-04-2019-0066/FULL/PDF.
63. Chiambaretto, P., and Dumez, H. (2012). The Role of Bundling in Firms' Marketing Strategies: A Synthesis. Recherche et Applications en Marketing (English Edition) *27*, pp. 91–105. https://doi.org/10.1177/205157071202700205.
64. Palm, J. (2018). Household installation of solar panels – Motives and barriers in a 10-year perspective. Energy Pol. *113*, 1–8. https://doi.org/10.1016/J.ENPOL.2017.10.047.
65. Curtius, H.C. (2018). The adoption of building-integrated photovoltaics: barriers and facilitators. Renew. Energy *126*, 783–790. https://doi.org/10.1016/J.RENENE.2018.04.001.
66. IEA-PVPS (2021). Snapshot of Global PV Markets - 2020.
67. Rietmann, N., Hügler, B., and Lieven, T. (2020). Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions. J. Clean. Prod. *261*, 121038. https://doi.org/10.1016/J.JCLEPRO.2020.121038.
68. Federal Statistical Office, F. (2022). Switzerland in 23 Infographics: Society, Economy, Territory and Environment.
69. Nielsen, K.S., Nicholas, K.A., Creutzig, F., Dietz, T., and Stern, P.C. (2021). The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions. Nat. Energy *6*, 1011–1016. https://doi.org/10.1038/s41560-021-00900-y.
70. Conseil fédéral (2013). Le Conseil fédéral adopte le message sur la Stratégie énergétique 2050. https://www.bfe.admin.ch/bfe/fr/home/actualites-et-medias/communiques-de-presse/mm-test.msg-id-50123.html.
71. Swissolar (2014). Il est enfin possible de consommer l'électricité produite sur son propre toit!. https://www.swissolar.ch/fr/services/medias/news/detail/n-n/solarstrom-endlich-selbst-verbrauchen/.
72. Etat de Genève (2018). Stratégie de l'électromobilité 2030.
73. Singer, J.D., and Willett, J.B. (1993). It's About Time: Using Discrete-Time Survival Analysis to Study Duration and the Timing of Events. J. Educ. Behav. Stat. *18*, 155–195. https://doi.org/10.3102/10769986018002155.
74. Kittner, N., Tsiropoulos, I., Tarvydas, D., Schmidt, O., Staffell, I., and Kammen, D.M. (2020). Electric vehicles. In Technological Learning in the Transition to a Low-Carbon Energy System: Conceptual Issues, Empirical Findings, and Use, in Energy Modeling, M. Junginger and A. Louwen, eds. (Academic Press), pp. 145–163. https://doi.org/10.1016/B978-0-12-818762-3.00009-1.
75. Louwen, A., Schreiber, S., and Junginger, M. (2020). Implementation of experience curves in energy-system models. In Technological Learning in the Transition to a Low-Carbon Energy System: Conceptual Issues, Empirical Findings, and Use, in Energy Modeling, M. Junginger and A. Louwen, eds. (Elsevier Inc.), pp. 33–47. https://doi.org/10.1016/B978-0-12-818762-3.00003-0.
76. Liu, Z., Song, J., Kubal, J., Susarla, N., Knehr, K.W., Islam, E., Nelson, P., and Ahmed, S. (2021). Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles. Energy Pol. *158*, 112564. https://doi.org/10.1016/j.enpol.2021.112564.

77. Weiss, M., Zerfass, A., and Helmers, E. (2019). Fully electric and plug-in hybrid cars - An analysis of learning rates, user costs, and costs for mitigating CO 2 and air pollutant emissions. J. Clean. Prod. *212*, 1478–1489. https://doi.org/10.1016/j.jclepro.2018.12.019.

78. Jakob, M., Reiter, U., Krishnan, S., Louwen, A., and Junginger, M. (2020). Heating and cooling in the built environment. In Technological Learning in the Transition to a Low-Carbon Energy System: Conceptual Issues, Empirical Findings, and Use, in Energy Modeling, M. Junginger and A. Louwen, eds. (Elsevier Inc.), pp. 189–219. https://doi.org/10.1016/B978-0-12-818762-3.00011-X.

79. IEA (2022). Electricity Market Report.

80. FSO, F.S.O. (2022). Population | Image |. https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases/infographics.assetdetail.22064052.html.

81. FSO, F.S.O. (2022). Number of occupants per dwelling. https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings/housing-conditions/persons.html.

82. Lammers, J., and Baldwin, M. (2018). Past-focused temporal communication overcomes conservatives' resistance to liberal political ideas. J. Pers. Soc. Psychol. *114*, 599–619. https://doi.org/10.1037/pspi0000121.

83. Allaire, J.J., Ellis, P., Gandrud, C., Kuo, K., Lewis, B.W., Owen, J., Russell, K., Rogers, J., Sese, C., Yetman, C.J., et al. (2022). Package "networkD3.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Open Science Framework under	https://osf.io/gserh/	
Software and algorithms		
R version 4.0.5	The R Project for Statistical Computing	www.r-project.org

RESOURCE AVAILABILITY

Lead contact

Further information should be addressed to and will be provided by the lead contact, Ulf Hahnel, ulf.hahnel@unibas.ch.

Materials availability

This study did not generate new unique reagents.

Data and code availability

- The dataset is available on the Open Science Framework: https://osf.io/gserh/
- The R code generated to analyze the data is available on the Open Science Framework: https://osf.io/gserh/
- Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

METHOD DETAILS

The survey was conducted online. Data was assessed from November 27, 2020 to December 21, 2020. Ethical approval was obtained from the ethical commission of the Faculty of Psychology and Educational Sciences of the University of Geneva before data collection. Regarding data collection, we had access to the client e-mail list of the entire population of detached and semi-detached house owners in the Geneva canton under the ethical agreement concluded between the University of Geneva and the electricity supplier company of the Geneva canton. We sent emails to all clients owning a house in the Geneva canton, inviting them to participate in our online study aiming at investigating public interest in renewable energy technologies (20'641 unique emails, see Table S1 supplementary material for more information). As compensation for participation, respondents could take part in a lottery with a prize of a CHF 200 shopping coupon from one of the three major grocery retailers of Switzerland.

In total, 2002 respondents completed the survey, out of which we excluded 12 observations because respondents did not remember the purchase year of owned technologies and 23 because they did not live in the Geneva canton. The final sample consisted of 1967 respondents. Regarding demographics and the representativeness of our sample, the sample consisted of more men (72% versus 50% of men) and was on average older than the Swiss population (38% versus 21% of individuals 65 years-old and over).[80] However, these differences can be accounted by our choice to target exclusively homeowners. In the French-speaking region of Switzerland to which Geneva canton belongs, 44% of owners are 65 years-old and older. Moreover, the number of people in the household in our sample was representative for Switzerland: 2.7 occupants per dwelling.[81]

Demographic information of the final study sample

	Sample N = 1967
Age	
18–64 years	62.1%
65 and over	37.9%
Gender	
Men	72.6%
Women	25.0%
Preferred not to answer	2.4%

(*Continued on next page*)

Continued	
Demographic information of the final study sample	
Income	
13'000 or less	45.0%
13'000–28'000	28.7%
28'001 or more	7.7%
Preferred not to answer	*18.6%*
Education	
Compulsory basic education	16.6%
Highschool/apprenticeship	19.8%
University/higher education	63.6%
Political orientation, 1-item[82]	
Liberals (score lower than the midpoint (1–4))	26.2%
Centrist (at the midpoint (5–6))	36.8%
Conservative (above midpoint (7–10))	22.2%
Preferred not to answer	*14.8%*
Number of people in the household	3 ± 1.2 people

Measurements

First, participants provided their informed consent to take part in the study and to provide their data. Afterward, they reported whether they adopted the low-carbon technologies of interest and for the adopted technologies in which year, i.e., photovoltaic solar panels, heat pump, stationary battery, hybrid car, and electric car. Second, we asked for each of the technologies owned, how much the experience with the given technology affected their interest in installing/buying each of the other technologies (5-point Likert scale: 1 = Much less interested, 7 = Much more interested, NA = if they installed the technology before). This data has been used for the analysis of subjective interest in co-adoption, complementing actual adoption and co-adoption data. Third, respondents reported their level of agreement to the following sentence: "I feel a personal obligation to contribute to the Swiss energy transition" (7-point Likert scale: 1 = Strongly disagree, 7 = Strongly agree) serving as our measure of *personal contribution*. Finally, we assessed demographic information including participants' political orientation,[82] which findings are reported in the supplementary material, Table S1 and S2: Model 3. After this study, participants had the opportunity to take part in an additional study, solely focusing on the adoption of solar systems (study not yet published).

Statistical analyses

Adoption and co-adoption determinants

To identify factors associated with the adoption of one technology and co-adoption of multiple technologies, we ran a multinominal logistic regression model to estimate the likelihood to adopt and co-adopt low carbon technologies. In the model, the dependent variable was coded as 0 when respondents did not adopt any low-carbon technology, as 1 when respondents adopted one low-carbon technology (*adoption*), and as 2 when respondents adopted two or more low-carbon technologies (*co-adoption*). By changing the reference level, we also contrasted *adoption* and *co-adoption*, allowing to test whether a certain factor plays a more important role for co-adoption compared to adoption decisions. As predictors of the model, we added demographics (i.e., age, education, income, number of people in the household, gender, and political orientation) and *personal contribution* (see measurements section for more details) as a measure of participants indicated personal obligation to contribute to the energy transition. In the baseline model age, education, income, number of people in the household, and personal contribution served as predictors (supplementary material, Tables S1 and S2: Model 1). Subsequently, we sequentially added gender and political orientation to the model (Tables S1 and S2: Model 2 and 3).

Technology diffusion patterns

To describe technology diffusion patterns, we analyzed technology ownership frequencies as well as the adoption rate by time. We further visualized co-adoption patterns by means of a Sankey graph[83] illustrating specific co-adoption pathways across time (see Figure 3). Sankey graphs are flow diagrams where flows can be traced through a series of stages. In our case, we illustrated co-adoption flows or pathways through technology adoption order (up to four).

Specific co-adoption effects

We applied event-history analyses[73] using Log Rank tests to compare Kaplan-Meier-Curves to test whether the adoption of a given low-carbon technology had a statistically significant impact on the adoption of other low-carbon technologies across time. We calculated Kaplan-Meier estimates indicating the probability that a technology adoption occurred in a given year contingent on whether or not another technology had been previously adopted or not. If no adoption of a technology occurred by the end of data collection, this event was entered into the analyses as censored, i.e., a parameter indicating the probability that the event did not occur.

We tested whether the cumulative probability of adopting the target technology differs between the group of previous adopters of another technology and non-adopters. To test whether potential co-adoption effects were driven primarily by co-adoption of technologies within close temporal proximity (i.e., within the same year) or by *lagged* co-adoption, we excluded co-adoption decisions within the same year and ran the same analysis on the subset of lagged co-adopters.

Technology-specific determinants

Finally, we looked at how adopting a technology changed self-reported interest in adopting other low-carbon technologies. With a stacked bar chart, we illustrated the percentages of respondents that reported an increase or decrease interest in co-adopting other technologies (see Figures 5A–5E).