SOCIOECONOMIC AND DEMOGRAPHIC FACTORS BEHIND THE DEPLOYMENT OF DOMESTIC PHOTOVOLTAIC AND SOLAR THERMAL SYSTEMS IN THREE SWEDISH MUNICIPALITIES

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ABSTRACT: The adoption of domestic photovoltaic systems has in numerous studies been proven to be influenced by peer effects and socioeconomic factors such as income, age, gender, education etc., which has led to irregular spatial installation patterns. Only a few studies regarding domestic solar thermal systems indicate that the same effect exist for this technology. However, the interaction between photovoltaic and solar thermal deployment and the similarities or differences in socioeconomic factors have not been investigated in detail so far. This study identifies the most prominent socioeconomic factors behind both domestic photovoltaic and solar thermal adoption in three different municipalities in Sweden, based on a complete set of 452 photovoltaic and 359 solar thermal collector systems installed until 2020, which was identified and classified by a method that uses machine learning and aerial imagery. A moderate (absolute Pearson correlation, $|\rho|$, > 0.3) to intermediate ($|\rho| > 0.5$) correlation between photovoltaic and solar thermal penetration was found on demographic statistical area level, and several of the previously reported influential socioeconomic factors for domestic photovoltaic installation were confirmed also for domestic solar thermal adoption in Sweden.
Keywords: Photovoltaic, Solar Thermal, PV Market, Solar Home System, Economic Analysis, Socioeconomic Analysis

1 INTRODUCTION

The interest in solar energy is growing rapidly in Sweden. In 2021, 26,500 grid-connected photovoltaic (PV) systems were installed with a combined installed output of 500 MW, which is an increase of 46% as compared to 2020 [1]. At the end of 2021, there were in total 92,359 grid-connected PV installations in Sweden, with a total installed capacity of 1,586 MW [1]. The positive development this year can partly be explained by the new green tax deduction for PV installations for private individuals, which was introduced in 2021 [2] and the rising electricity prices preceding the Russian invasion of Ukraine. The increasingly integrated European electricity system means that electricity prices will probably be more equalized across Europe [3,4], which means that electricity prices higher than Swedish end-consumers experienced in the last decade will become the norm the coming years.

The interest in the other major solar energy technology, solar thermal (ST), has varied the last decades in Sweden. Between 2000 and 2011, an investment subsidy for private individuals and small-scale systems was in place [5], and a majority of the current Swedish ST systems (usually with a size of less than 15 m^2) were installed in that period. In the last decade, the Swedish ST market in Sweden has declined due to low profitability [6], as there is no direct support system for ST systems at the time of writing. The shrinking market is in line with findings about the economics of unsubsidized ST in other European countries [7]. However, a majority of the previous installed systems remain in use and there is still an estimated total ST area of about 450,000 m^2 in operation in Sweden [6].

The roll out of new decentralized granular technologies, such as PV and ST, has been observed as faster than more bulky energy technologies, as they profit from shorter diffusion time scales, more attractive risk profiles for investors, and stronger potential for cost and performance improvements [8]. In addition, the diffusion pattern is usually highly influenced by social interactions, so called peer effects [9], and by socioeconomic factors. PV adoption has been found to be concentrated in certain areas or clusters [10–28]. This cluster tendency can partly be explained by peer effects, leading to an effect where the probability of additional PV installations is higher where the number of existing PV systems is high (with a certain time lag) [12–16,19,22,24–26,28–32].

In addition to peer effects, difference in socioeconomic and demographic factors of the inhabitants in different areas also affect the spatial distribution of domestic PV. Spatial, demographic and socioeconomic differences in PV installation patterns have been studied in countries such as Australia [10,33], Belgium [11], Canada [34], China [12,35], Denmark [36], Germany [13–16], Greece [37], Japan [38], the Netherlands [17], Sweden [29–31,39], UK [18–21,32] and US [22–28,40]. It has been shown that identified factors can be highly contextual and that they can vary both between and within countries [10,15,21,26,28,40]. Previous such international studies have often relied on qualitative methods based on survey studies/interviews [29–31,34,36,37,41] and/or by qualitative methods based on aggregated data over a larger area, i.e., an administrative region [14,38,42], Municipality [29], NUTS3[1] [16,19], postal or zip code [10,17,20,22,23,32,33,40], statistical sector[2] [11,13,39] or census block[3] [24,26–28,40,43].

Socioeconomic and demographic studies about the ST technology are scarce in comparison. Some literature have treated awareness, acceptance and motives [35,44,45], but when it comes to important socioeconomic factors for domestic ST adoption it has mainly been studied in Germany in the beginning of the 20th century [46–48]. An exception is [49], which through a discrete choice experiment survey investigated customer preferences of ST and PV in Boston and Atlanta and found an overall

[1] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for the purpose of the collection, development and harmonization of European regional statistics

[2] Statistical sectors are very disaggregated local areas – typically a set of streets – grouped by socioeconomic, urban and morphological structural features.

[3] A census block is the smallest geographic unit used by the United States Census Bureau

general preference of PV over ST systems in both cities.

However, the spatial distribution of ST has so far not been investigated thoroughly, and only evidence of cluster tendencies on a high regional level has been presented in the scientific literature [42,50]. In addition, the interaction between ST and PV system distribution has not been studied.

Since the expansion of PV in Sweden is somewhat late in an international comparison, early research on the diffusion of PV in Sweden has primarily focused on qualitative methods as the statistical basis has been limited [29,30,51–54]. Through survey and interview studies, the influence of adopters on others through a so-called word-of-mouth process [29,31], and local organizations have been identified as important [29]. Especially local utility companies that bought excess electricity, offered turnkey solar systems and held information meetings about solar energy have been considered influential [29,31]. Late adopters have been found to have stronger financial, rather than environmental, motives than early adopters [51]. As the PV technology has become more common in Sweden, quantitative methods have been used in later research [31,39,55]. In one of those studies, it was investigated how socioeconomic parameters influenced the willingness to install PV systems in Uppsala municipality [39]. In this study it was found that parameters such as land ownership, average income, number of cars, age and employment rate had a large impact on the willingness to invest in PV. In a survey study, it was found that peer effects raise the likelihood of adopting PV, as does a higher subsidy from the state [31]. This article also concluded that males are marginally more likely to adopt PV, older people are marginally less likely, and that income is not a significant predictor.

The main novelty of this quantitative study is that the complete dataset contains both ST and PV systems, and therefore makes it possible to analyse the difference between the two solar energy technologies when it comes to spatial adoption and the underlaying socioeconomic and demographic factors. The motive is that an end-customer's knowledge about one technology (in Sweden ST as this was mainly built a decade before the major roll-out of PV), familiarity of a similar technology has been found to play a role in PV adoption [56]. In addition, indicative evidence of passive peer effects through spill over between PV and ST has been found in Sweden [29].

2 METHOD

The aim of this study is to analyze different socioeconomic and demographic factors' relation to and impact on solar energy systems in Sweden. This section presents the methodology of the creation of a solar energy system inventory and the choice of geographical area, data management, analysis methods and made assumptions.

2.1 Creation of solar energy systems data set

A limited geographical area of three Swedish municipalities was chosen to be able to keep a preferable high granularity [27]. Local factors have previously been shown to influence the rate of diffusion of PV in Sweden [29], and the choice of the three municipalities Falun, Knivsta and Uppvidinge was done on purpose so that three different types of municipalities in terms of size, characteristics and location were covered.

Falun is a spatially large municipality, 2,040 km^2, in central Sweden with 59,837 inhabitants in 2020 [57]. The municipality is centered around the regional center of the town Falun, but also contain ten smaller surrounding villages, and 87.3% of the inhabitants live in these eleven urban areas of the municipality.

Knivsta is a relatively spatially small municipality, 295 km^2, located close and between the two major Swedish cities Stockholm (the capital of Sweden) and Uppsala (the fourth largest city). The two urban areas in the municipality, Knivsta and Alsike, where 72.8% of the population lives, are typical commuter resorts. The average age of the 19,818 inhabitants is one of the lowest in the country [58].

Uppvidinge is a 1,178 km^2 large municipality in the southern part of Sweden with 9,449 inhabitants, which is dominated by agriculture land and forest. The municipality lacks a major town, but 74.3 % lives in urban areas including 2700 inhabitants in the regional center Åseda [59].

In this study Falun represent a large urban/rural municipality centered around a major regional city, Knivsta a suburban municipality and Uppvidinge a rural municipality. Some general socioeconomic key figures of the three municipalities are summarized in Table I.

Table I: Population density [inhabitants/km^3], average age [years], average monthly earned income for all inhabitants >20 years [SEK/month] and employment rate [%] for Falun, Knivsta and Uppvidinge municipalities in 2020 [58,60].

	Pop. density	Avg. Age	Avg. Income	Employ-ment
Falun	29.2	42.4	27,358	82.6
Knivsta	32.2	36.9	33,408	87.2
Uppvidinge	16.2	43.5	23,617	81.6

For the actual creation of an inventory of solar energy systems, a slightly modified version of the open access DeepSolar machine learning and aerial imagery PV mapping framework [61,62] was implemented and used to scan Ortophoto images of the municipalities. The identified systems were saved as polygon objects and analyzed with the QGIS3 software.

The identified PV systems were cross-checked with the local Distributed Systems Operators' (DSO) registers of grid-connected PV. In some rare cases, visual inspection through orthophoto images was not enough to remotely verify existing solar energy systems, uncertainties regarding type of solar energy system, design and/or location. For these systems, physical on-site inspections were carried out to complete the inventory. Through this procedure, a complete set of all PV and ST systems could be compiled for the three municipalities.

By using the coordinates of the identified solar energy system polygons as keys for available geodata services from the Swedish Land Survey, all the located PV and ST systems were connected to the unique Swedish property designations of the real properties (the legal division of land) within which they were installed.

The advantage of this method is that a complete inventory of PV and ST systems that include systems installed without any subsidies can be created. As a comparison, the registers of the DSO's do not contain any ST systems nor any off-grid PV systems, and the information about the location are on the level of "somewhere within the real property".

The inventory of solar energy systems contained all completed systems at the time of the aerial photos, which was (depending on spatial location in the municipality) in Falun the 2020-05-21, 2020-06-11 or 2020-06-14, in Knivsta the 2019-07-19 or 2019-07-20 and in Uppvidinge the 2020-05-31 or 2020-06-01. To enable an analysis of only domestic PV and ST, all solar energy systems on real properties owned by companies were excluded from the dataset. In addition, households that acquired the property after the aerial photos were taken, were removed from the set, as no socioeconomic information about previous owners were available. In addition, some specific uncertain ownership situations, like if the owner of a real property lived outside of the municipality, real properties with two or more owners not living at the same address, several owners all living in the municipality but not at the real property of the solar energy system, were also removed from the set.

2.2. Socioeconomic and demographic data

With the property designation as a key, socioeconomic information of the specific households with solar energy systems could be extracted from the Swedish authorities Statistic Sweden (the Swedish government agency operating responsible for producing official statistics for decision-making, debate and research) and the Swedish Land Survey, along with the company Ratsit AB (which produces a Taxation calendar that contains information about income and capital for individuals).

In addition to household level, demographic data were available at two more aggregated levels. The most aggregated level was the municipality level. The second most aggregated level was, just as in [39], the fixed demographic statistical areas (DeSO) that Statistic Sweden divide all municipalities into. The size of a DeSO is determined based on population and building concentration and can therefore have a very different spatial size, i.e., usually around 1,500 inhabitants, but can vary between 600 and 3,500 [63]. There are three different categories of DeSOs:

1. Rural – Areas mainly located outside larger population concentrations or urban areas.

2 Urban – Areas mainly located in a population concentration or urban area but not in the municipality's regional center.

3. Center – Areas mainly located in the municipality's regional urban center.

Fig. 1 shows the orthophoto of Uppvidinge municipality, with the six different DeSOs included, along with all PV and ST systems as an illustrative example.

The total number of DeSOs and distribution between the different categories is displayed in Table II for the chosen municipalities, along with the distribution of inhabitants and households.

Previous research has identified systems through different approaches and analyzed data at different levels and granularity. With the approach of this study the granularity available was on household level for some socioeconomic and demographic factors, and on either DeSO or municipality level for correlation analyses.

2.3 Dependent and independent variables

In order to evaluate different socioeconomic and demographic factors' relation to, and impact on, private residential solar energy deployment, PV or ST density in terms of number of systems per households were chosen as the dependent variables in this study.

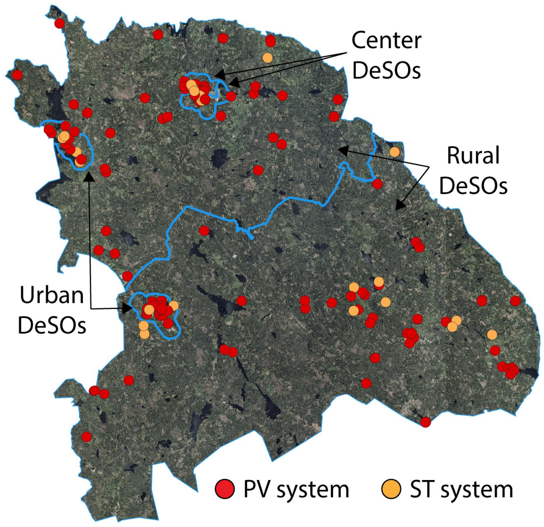

Figure 1: The orthophoto image of Uppvidinge municipality, with the different DeSO areas framed by blue boarders and all existing PV and ST systems by June 2020.

Table II: The of number of demographic statistical areas (DeSOs), inhabitants, households and average number of inhabitants per household in the different DeSOs types 'Rural', 'Urban' and 'Center' in Falun, Knivsta and Uppvidinge municipality, respectively.

	Rural	Urban	Center	Total
Number of DeSOs				
Falun	6	5	26	37
Knivsta	3	0	7	10
Uppvidinge	2	2	2	6
Number of inhabitants				
Falun	9,641	7,925	41,962	59,528
Knivsta	5,249	-	13,857	19,106
Uppvidinge	3,673	3,052	2,773	9,498
Number of households				
Falun	4,119	3,648	20,222	27,989
Knivsta	2,082	-	5,463	7,545
Uppvidinge	1,724	1,448	1,219	4,391
Average number of inhabitants per household				
Falun	2.3	2.2	2.1	2.1
Knivsta	2.5	-	2.5	2.5
Uppvidinge	2.1	2.1	2.3	2.2

The analysed independent variables were chosen based on available data and previous research (summarized in [21,64]) and were; (1) Age, (2) Sex, (3) Birth origin, (4) Education level (5) Employment rate and (6) Different economic conditions, summarized in Table III.

Age is represented through five independent variables corresponding to percentage of the population in the age groups of *0–15*, *16–24*, *25–44*, *45–64* and *>65* years.

The variable *Sex*, the distribution between the sexes, is expressed as the percentual share of males.

Birth origin as an independent variable is referred to as *BOri* and represents the percent of individuals which are born in Sweden.

Education level is denoted *Educ* and represents the percentage of the population with a post high school education.

Table III: Chosen socioeconomic factors with a detail level description, available granularity level and source of the data, where SLS is short for Swedish Land Survey.

	Detail level	Granularity			Source
		Municipality	DeSO	Household	
Population	Total number of households	X	X	-	Statistics Sweden
	For all of age >20	-	-	X	Ratsit
Age	7 age groups	X	X	-	Statistics Sweden
	For all of age >20	-	-	X	Ratsit
Sex	Total distribution	X	X	-	Statistics Sweden
	For all of age >20	-	-	X	Ratsit
Birth origin	Sweden, Europe, RoW	X	X	-	Statistics Sweden
Education	Age 25-64	X	X	-	Statistics Sweden
Employment	Age 20-64	X	X	-	Statistics Sweden
Average income	Age ≥20	X	X	-	Statistics Sweden
	Age ≥20	-	-	X	Ratsit
Economic standard	4 groups, age 20+	X	X	-	Statistics Sweden
Property purpose	General and detailed	-	-	X	SLS
Property owner	Taxed owner	-	-	X	SLS
Tax value	Buildings, land and total	-	-	X	SLS

Employment rate as an independent variable is denoted *Emp* and expressed as the percentage of the population being employed.

The economic situation of the households is represented by several independent variables that are gathered from the different data sources listed in Table III. The first is average income, *AInc*, of the DeSO, defined as the aggregated taxable earned income, which refers to income from employment, business/entrepreneurship, pension, sick pay and other taxable transfers. The second variable is the average economic standard, *EcSt*, which is calculated as disposable income per consumption unit.

2.4 Correlation analysis

The Pearson correlation coefficient was calculated for all variables. In this study, strong correlation was defined as absolute values of the correlation coefficient of >0.7, intermediate correlation for values of 0.5–0.7, moderate for values of 0.3–0.5 and weak correlation for absolute values of 0.1–0.3.

Presenting Pearson correlation coefficients in a matrix also allow for a collinearity analysis between the independent variables. Collinearity refers to the non-independence of variables and occurs when two variables correlate due to mutual underlying factors, or when the data used is compositional. If the absolute value of the correlation coefficient between two independent variables is higher than 0.7, it indicates a severe collinearity [65].

3 RESULTS

In this section the results are presented, which includes a general description of the distribution of the 814 domestic solar energy systems (Section 3.1), a correlation analysis on the socioeconomic and demographic parameters (Section 3.2) in comparison to similar studies (Section 3.3) and finally, some characteristics on households owning a solar energy system (Section 3.4).

3.1 The domestic solar energy system data set

The final data set of domestic solar energy systems is summarized in Table IV. The table also include the number of households that have both ST and PV systems on their roof.

Table IV: Number of domestic PV and ST systems in Falun, Knivsta and Uppvidinge municipalities, along with number of households that have installed both a PV and a ST system.

	#PV	#ST	Total	*PV&ST*
Falun	276	287	563	*16*
Knivsta	103	49	152	*7*
Uppvidinge	73	23	96	*1*
Total	452	359	811	*24*

With regards to the distribution of systems in the different DeSO types, 201 of the 452 PV systems (44.5%) were found in different 'Rural' DeSOs, 54 (11.9%) in the 'Urban' DeSOs and 197 (43.6%), in the 'Center' DeSOs of the municipalities. Likewise, 161 of the total 359 ST systems (44.8%) were found in the different 'Rural' DeSOs, 66 (18.4%), in the 'Urban' DeSOs and 132 (36.8%), in the 'Center' DeSOs of the municipalities. Domestic PV systems were identified in 47 out of the 53 DeSOs and domestic ST systems were identified in 45 of the DeSOs. The DeSOs without solar energy systems were found to all be of type 'Center'. When it comes to lack of domestic PV system, all those DeSOs were in Falun, while one of the 'Center' DeSOs without a domestic ST was in Knivsta and the rest in Falun.

The excluded domestic solar energy systems, motivated by non-existing or uncertain background data, is judged to have a small effect on the results, as this number is small as compared to the final data set. 37 systems were omitted in Falun, 8 in Knivsta and 19 in Uppvidinge, as a result of the owning household living outside the municipality or acquired the real property after 2020-12-31. In addition, 12 systems were omitted in Falun due to lack of data or definition difficulties.

The number of domestic solar energy systems per 1,000 households are presented in Fig. 2. As can be seen, the concentration of both PV and ST systems per 1,000 households are higher in the 'rural' areas of the municipalities as compared to the 'urban' or 'center' areas. The reason is likely that many more households in the 'urban' and 'center' areas live in multi-family houses, which makes it impossible to own a private residential solar energy system.

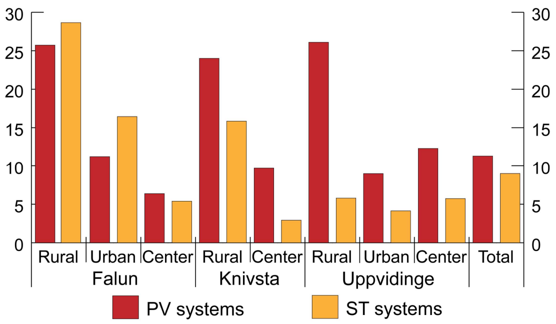

Figure 2: The average number of private residential PV or ST systems per 1,000 households in the different type of DeSOs in Falun, Knivsta and Uppvidinge.

Another observation in Fig. 2 is that the concentration of ST systems was found to be higher in the 'rural' and 'urban' areas of Falun, as compared to the concentration of PV systems, which is the opposite to the PV/ST concentration relation in the other municipalities. This indicates that local factors probably have had an important role in driving the diffusion of ST systems in Sweden as well, just as Palm found for PV systems [29].

3.2 Demographic correlation and collinearity results

The correlation analysis based on the Pearson correlation coefficient showed the relation between the dependent variables, number of PV systems per household, *#PV*, and number of ST systems per household, *#ST*, and the independent demographic variables, presented in Section 2.3. The correlation matrix presented in Fig. 3 represent the whole domestic data set. The matrix in Fig. 3 is based on installed PV systems per household, *#PV*, in each 47 DeSOs with a private residential PV system and socioeconomic and demographic statistics for each DeSO. However, in an evaluation of the result before creating the matrix, two out of the 47 DeSOs that contained PV systems were found to be outliers (one 'rural' in Falun and one 'rural' in Uppvidinge) with 0.063 and 0.046 PV systems per households, respectively, as compared to the rest of the DeSOs, which exhibit penetration levels between 0.001–0.033 PV systems per household. Omitting these two outlier DeSOs resulted in a dependent variable based on installed PV systems per household, *#PV**, in the other 45 DeSOs.

#PV	1	-												
#ST	0.36	0.61	1											
0–15	-0.09	0.06	-0.24	1										
16–24	-0.44	-0.31	-0.43	0.16	1									
25–44	-0.41	-0.42	-0.51	0.50	0.21	1								
45–64	0.52	0.59	0.58	-0.39	-0.35	-0.74	1							
>65	0.18	0.00	0.31	-0.90	-0.34	-0.67	0.34	1						
Sex	0.56	0.50	0.36	0.01	-0.23	-0.20	0.51	-0.07	1					
BOri	0.32	0.36	0.56	-0.07	-0.51	-0.35	0.42	0.19	0.05	1				
Edu	-0.22	-0.06	-0.26	0.38	0.28	0.23	-0.22	-0.39	-0.49	0.28	1			
Emp	0.15	0.35	0.27	0.34	-0.35	-0.07	0.19	-0.21	-0.02	0.75	0.50	1		
AInc	0.00	0.21	-0.07	0.66	0.14	0.21	-0.01	-0.65	-0.07	0.33	0.76	0.71	1	
EcSt	0.18	0.43	0.06	0.38	-0.04	-0.05	0.27	-0.37	0.01	0.39	0.66	0.71	0.85	1
	#PV	#PV*	#ST	0–15	16–24	25–44	45–64	>65	Sex	BOri	Edu	Emp	AInc	EcSt

Figure 3: Correlation matrix with Pearson correlation coefficient between installed PV and ST systems per household and different demographic independent factors for all DeSOs with installed systems in the municipalities Falun, Knivsta and Uppvidinge combined. The colors match the strong, intermediate, moderate and weak correlations with yellow→green for the positive and yellow→red for the negative correlations.

As Fig. 3 display, negative collinearity in this matrix were found between the independent variables; (1) age groups *0–15* and *>65*, and (2) age groups *25–44* and *45–64*. Positive collinearity was uncovered for (1) employment, *Emp*, and birth origin, *BOri*, (2) education level, *Educ*, and average income, *AInc*, (3) employment, *Emp*, and average income, *AInc*, (4) employment, *Emp*, and average economic standard, *EcST*, and (5) average income, *AInc* and average economic standard, *EcST*.

As the main contribution to the literature it should be noted that a moderate positive correlation (0.36) was discovered between *#PV* and *#ST*, which increased to an intermediate positive correlation when the two outlier DeSOs were omitted (0.61). Furthermore, an intermediate positive correlation was revealed between both *#PV* and *#ST* and the age group *45–64*, while the age groups of *16–24* and *25–44* both explicit a moderate to intermediate negative correlation to solar energy system penetration on a DeSO level. The percentage of men in a demographic area also seem to have a positive effect on solar energy deployment by demonstrating intermediate positive correlation for *#PV* and moderate positive correlation for *#ST*. For the other independent demographic variables, the correlation was found to be weak or non-existing, except if the two DeSOs with exceptionally high PV penetration were omitted, which resulted in that the correlation between *#PV** and employment along with average economic standard rose to moderate positive correlation.

The presented correlation matrix in Fig. 3 does not take differences between the municipalities in general demographic terms of, e.g., overall income and education level, into account, which might have resulted in a weaker correlation between the different variables. Thus, Pearson correlation coefficients between number of PV systems per household and each independent variable are presented for the three municipalities separately in Fig. 4.

#PV	#ST	0–15	16–24	25–44	45–64	>65	Sex	BOri	Edu	Emp	AInc	EcSt
Falun	0.49	-0.08	-0.38	-0.41	0.49	0.19	0.66	0.43	-0.24	0.16	0.03	0.09
Knivsta	0.45	-0.24	-0.50	-0.68	0.69	0.37	0.74	0.59	-0.20	0.27	0.00	0.62
Uppvidinge	-0.57	-0.15	-0.81	-0.51	0.63	0.38	-0.22	0.87	0.62	0.56	0.42	0.79
#ST	#PV	0–15	16–24	25–44	45–64	>65	Sex	BOri	Edu	Emp	AInc	EcSt
Falun	0.49	-0.18	-0.43	-0.58	0.65	0.31	0.56	0.55	-0.41	0.31	-0.02	0.14
Knivsta	0.45	-0.33	-0.65	-0.45	0.73	0.33	0.81	0.55	-0.76	0.14	-0.16	0.22
Uppvidinge	-0.57	0.12	0.26	0.24	-0.25	-0.18	0.32	-0.64	0.12	-0.65	-0.70	-0.62

Figure 4: Pearson correlation coefficients between number of installed PV systems per household (top part) respective number of installed ST systems per household (bottom part) and the different demographic independent factors for all DeSOs with installed PV systems in the municipalities Falun, Knivsta and Uppvidinge.

#PV	#ST	0–15	16–24	25–44	45–64	>65	Sex	BOri	Edu	Emp	AInc	EcSt
Rural	-0.47	-0.13	-0.52	-0.28	-0.08	0.31	0.38	0.21	-0.01	-0.08	-0.13	-0.10
Urban	0.57	-0.56	0.07	-0.62	0.51	0.35	-0.37	0.28	0.34	0.52	0.56	0.59
Center	0.65	0.27	-0.11	-0.44	0.49	-0.13	0.54	0.35	0.11	0.35	0.33	0.45
#ST	#PV	0–15	16–24	25–44	45–64	>65	Sex	BOri	Edu	Emp	AInc	EcSt
Rural	-0.47	-0.07	0.26	0.04	0.06	-0.05	-0.16	0.65	0.17	0.21	0.09	-0.15
Urban	0.57	-0.35	-0.47	-0.80	-0.09	0.82	-0.70	0.82	0.89	0.83	0.91	0.51
Center	0.65	-0.03	-0.22	-0.58	0.60	0.16	0.35	0.44	0.02	0.30	0.12	0.28

Figure 5: Pearson correlation coefficients between number of installed PV systems per household (top part), respective, number of installed ST systems per household (bottom part) and the different demographic independent factors for all 'rural', 'urban' and 'center' DeSOs with installed PV systems in the municipalities Falun, Knivsta and Uppvidinge.

The result presented in Fig. 4 is relatively consistent between the municipalities when it comes to the correlation between *#PV* and the age groups and birth origin, but inconsistent regarding the sex and education, with Uppvidinge found to have an opposite correlation compared to Falun and Knivsta for these factors. Strong and intermediate correlation is found for average economic standard in Knivsta and Uppvidinge, whilst only weak in Falun.

For the number of households with ST systems the results are quite consistent with that of PV in Knivsta and Falun. Standing out is the strong negative correlation between ST system penetration and high education and that employment have changed from negative to positive correlation. The *#ST* in Uppvidinge on the other hand show quite different correlation as compared to both the two other municipalities, and the situation for *#PV*. One reason could be that the statistical base for Uppvidinge is the weakest, with only 23 ST systems and 6 DeSOs as compared to 287 ST systems in Falun and 49 in Knivsta, and 37 respective 10 DeSOs.

In Fig. 5, the Pearson's correlation coefficient between *#PV* and *#ST*, respectively, and the independent demographic variables is presented for the three types of DeSOs. For PV, there is no consistency between almost all variables, as uniformity is only shown for the variables *25–44* years and birth origin. One trend that can be observed is that the correlation coefficients are more similar between 'urban' and 'center' area DeSOs, while 'rural' DeSOs show an opposite trend as compared to the two other types.

For *#ST*, a few consistencies are found for all the DeSOs, namely birth origin, education, employment and average income. Otherwise, it is hard to distinguish any clear trends. There are similarities between 'rural' and 'urban' areas for some independent variables and between 'urban' and 'center' for some other variables. Commonly, the strongest correlations are found for both PV and ST in the 'urban' DeSOs.

3.3 Comparison with the literature

The result of the demographic correlation analysis, which resulted in non-existing or weak correlation with PV and ST penetration and income on the aggregated DeSO level, are in line with several quantitative studies that have reported statistically weak or insignificant impact of the average income for larger spatial areas [11,14,16,19,32,33,38] or even a negative effect [13,21,34]. Furthermore, just as in this study, it has also previously been shown that average economical standard, or accumulated capital, can be a demographic factor that is of higher importance as compared to the average income on an aggregated area level [26].

An intermediate positive correlation between number of, both PV and ST systems per household, and age group *45–64* years was uncovered, just as previously reported in the municipality of Uppsala [39], which indicates that a population with a higher percentage of people of this age is more likely to install solar energy systems. The opposite seems to be the case for young and middle-aged adults, as the age groups of *16–24* and *25–44* both present a moderate to intermediate negative correlation to solar energy system penetration on a DeSO level. It should be noted that the average age in Knivsta is lower (36.9 years) compared to Falun (42.4 years) and Uppvidinge (43.5 years), which might skew the result in Fig. 3 to some extent. These findings are to a large extent in line with previous research, where i.e., [22,23] in the US and [17] in the Netherlands, recognized negative correlation for age groups between 20–45 and >65 on a zip code level. Also, in Australia [33], Germany [16], Greece [37], and the UK [32], higher share of middle-aged people in an area has been found to increase PV adoption. Regarding the age group >65 years, [45] concluded that retired people in the UK are less motivated to complement their heating system with a PV or ST system due to the high upfront cost and long pay-off time. In addition, [48] found that solar heating adoption propensity declined with the age of the household head in the early market in Germany. However, the literature is not consistent as [11,40] found that household age was less important than previously shown.

The variable *sex* demonstrated intermediate positive correlation with both installed PV systems (0.56 or 0.50) and age group *45–64* years (0.51) in this study. The latter indicates a higher percentage of males in this age group in the three municipalities investigated, while the former could be an indication that a population with higher percentage males are more likely to install PV systems, which was also found in [22] on zip code level in California. However, for Flanders, Belgium, [11] found weak evidence of higher PV adoption rates for males in general, but that single male households are significantly more likely to adopt PV as compared to single female households.

The correlation between the number of inhabitants born in Sweden and solar energy system adoption was found to be moderate positive for PV (0.32 or 0.36) and intermediate positive for ST (0.56) as illustrated in Fig. 3. However, the *BOri* variable shows strong positive correlation (0.75), hence collinearity by the implemented definition, with the independent variable employment. For the municipalities evaluated separately in Fig. 4, the result is stronger for PV (0.43–0.87) and with a consistent opposite correlation of employment. The consistent strength and opposite correlation with employment also holds for ST system penetration, with a notable outlier result in Uppvidinge, where both birth origin and employment have an intermediate negative correlation of -0.64 and -0.65, respectively. The consistency in the correlation result between these two independent variables is also visible in Fig. 5, where the DeSOs are evaluated separately, but not as apparent as in Fig. 4. In summary, the consistency between these two variables could indicate that it is not Sweden as birth origin of the inhabitants per se that increases likelihood of adoption of PV. It is rather the high employment that increases the likelihood of PV adoption, and that it is the collinearity between these two social factors in Sweden that is the reason for the result. This hypothesis is to some extent strengthened by the results of [22,23,26,28,40] in the US, where racial variables where generally not statistically significant, with only weak evidence of more adoption when there is a higher percentage of white people in an area in [23,26,28,40]. On the other hand, [11] states that an increase of the number of foreigners by one percentage unit point reduces the number of PV installations by 0.38% in Belgium for the time period 2006–2012.

Regarding *Emp*, in addition to *BOri,* collinearity was obtained with the two economic conditions *AInc* and *EcSt*, which is an expected result. The correlation to installed PV and ST was found to be weak for the municipalities combined, but stronger for PV (-0.16–0.56) when analysed separately, which exemplifies the different employment rates in the municipalities. In 2020, Falun and Uppvidinge had an employment rate of 81.6% and 82.6%, respectively, while in Knivsta it was 87.2%. Knivsta, with a positive correlation of 0.27 for employment rate, is the neighbouring municipality of Uppsala, where an earlier study [39] found a positive correlation for the same dependent and independent factors of 0.3. An evaluating of the result for the different type of DeSOs show stronger positive correlation in the 'urban' and 'center' areas, while the 'rural' DeSOs show a much weaker correlation between employment and both PV and ST adoption. Compared to earlier international studies, [26] did not find any significant correlation between employment rate and installed PV systems, while [16,27] identified a positive correlation. Thus, the weak positive correlation presented in this study can be assumed to be in line with previous research. However, a difference between the different types of DeSOs can be identified. Since the average employment rates are similar in the three DeSO types within each municipality, this difference indicates that the employment rate has a larger impact on adoption of PV systems in 'urban' and 'center' DeSOs.

The independent variable education was discovered to have a weak negative correlation to both installed PV and ST systems, and an expected strong positive correlation (demonstrating collinearity) to average income (0.76). When the municipalities were evaluated separately, high education level demonstrated negative correlation with both PV and ST deployment in Falun and Knivsta (for ST in Knivsta the negative correlation was even stronger), while positive correlation in Uppvidinge. The results for different types of DeSOs show a positive correlation for 'urban' and 'center' area DeSOs, indicating that a higher education level increases the likeliness of installing PV in these areas. The results presented by [23,27,40] showed a positive impact between higher education level in an aggregated area and PV adoption in the US, and the same type of findings have been presented for Canada [34], Denmark [36], Germany [16], the UK [19], and another municipality in Sweden [39], while [11] found a negative impact by a higher share of college degrees in Belgium. The investigated areas in [21], with a negative correlation between PV deployment and education, were found to have a general lower level of education, which was assumed to be an explanation of the result. The education correlation for 'rural' DeSOs was found to be -0.01, and in Falun and Knivsta the average education levels are in general lower in the 'rural' DeSOs as compared to, for example, the 'center' DeSOs, which, if following [21], might explain the result. The average education level is more even, and in general lower, in the different DeSO areas in the rural municipality of Uppvidinge, which also might explain the positive correlation for the municipality in contrast to the other two.

3.4 Solar energy owning household characteristics

Data on the average age and average time living at the residence of each household was available through Ratsit, and a summary is presented in Table V, along with average age of all residents in the municipalities. The statistical comparison shows a slightly higher average age of the households with PV as compared to the average age of households with ST, and that owners of both PV and ST are older than the average age of all inhabitants in each municipality. This agrees with the finding that households with an average age of >40 are overrepresented as PV owners in Denmark [36], but somewhat contradictory to a Swedish survey study where age was found to have a negative effect, though not highly significant [31]. The result in Table V strengthens our correlation result on an aggregated DeSO level, where the age group *45–64* was found to have an intermediate positive correlation.

Table V: Average residence time of households with PV or ST systems in years, along with the average age of inhabitants with an age >20 years in households with PV or ST systems and the average age of all inhabitants of >20 years in Falun, Knivsta and Uppvidinge municipalities.

	Res. time PV	Res. time ST	Age PV	Age ST	Age total
Falun	22.1	22.6	57.9	57.9	51.8
Knivsta	17.1	17.8	54.4	52.3	48.3
Upp.	23.7	28.6	58.9	55.4	53.3

In addition, the average time of living at the residence for households that have installed a PV system was found to be around 20 years, with slightly longer residence times for ST owning households.

The summary of households with solar energy systems includes information about the average sex of the inhabitants, in this study expressed in terms of percentage of males. The average sex of households with solar energy system was calculated for members >20 years, while the average sex for the municipality only was available for inhabitants of all ages. Hence, there is a slight mismatch in the comparison. The results are presented in Table VI.

Table VI: Average sex in terms of share of males for households with PV and ST systems and average sex of all residents in the municipalities for Falun, Knivsta and Uppvidinge.

	Average sex PV	Average sex ST	Average sex total
Falun	49.9%	54.8%	49.6%
Knivsta	51.1%	51.4%	51.0%
Uppvidinge	54.8%	55.1%	52.3%

The conclusion is that the percentage of males in the households with PV systems was just slightly higher than the average in all three municipalities, and that in turn percentage of males in the households with ST systems was even a little bit higher. This result is in line with a previous Swedish survey study about PV adoption [31], our findings and previous research on aggregated level, and with a study from Denmark, that revealed that registered owners of PV were more often men (85.8%) and that the decision of buying a PV system was substantially more often made by men [36]. It has also been concluded that men in Germany are more prone to invest in ST systems [48].

The average income of the households with a PV or ST system was compared to the average income of the separate DeSOs. The difference in average income in percent for each DeSO is presented in Fig. 6 for households with PV systems and in Fig. 7 for households with ST systems.

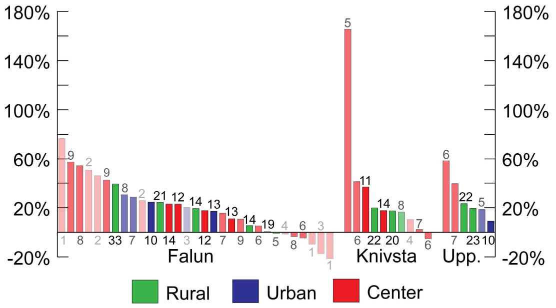

Figure 6: Difference in percent between the average income of households (average for all persons with an age of ≥20 years) with PV systems in a DeSO and the respective average in the same DeSO. The number above and below the bars represents the number of households with a PV system in the private residential set for each DeSO, and DeSOs with <10 respectively <5 households with PV are weakened in color to illustrate the less statistical strength of these results.

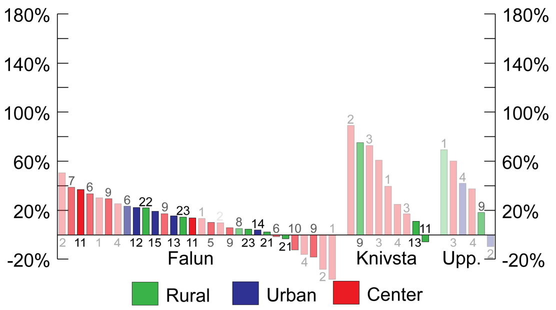

Figure 7: Difference in percent between the average income of households (average for all persons with an age of ≥20 years) with ST systems in a DeSO and the respective average in the same DeSO. The number above and below the bars represents the number of households with a ST system in the private residential set for each DeSO, and DeSOs with <10 respective <5 households with ST are weakened in color to illustrate the less statistical strength of these results.

The results show that a majority of the analyzed households were found to have a higher average income than the average income of all inhabitants in respective DeSO, and thereby confirm the importance of income as a factor for the distribution of PV, which has been recognized in many other countries [10,11,17,20,22,23,26–28,36,37,39,41,43] and in Germany for ST [46,47].

In Falun, the difference in income for all households with PV as compared to the average income in the municipality was 22%, in Knivsta 28% and in Uppvidinge 29%. Fig. 6 and Fig. 7 also show that the highest percentual differences were found in DeSOs of 'center' type for all three municipalities.

This observation is probably related to higher percentual share of people living in apartments in the 'center' DeSOs, and that those that can afford a single-family house (and thereby can install a private residential PV system) in these attractive areas have a higher income than those that live in the apartments. The fact that relatively more households in the 'urban', and especially 'center' DeSOs likely live in apartments probably also influences the correlation analysis of the demographic parameters. This might explain some of the inconsistency between correlation coefficients in Fig. 5, between, above all, the 'rural' compared to the 'urban' and 'center' DeSOs.

A closer analysis of the PV owners with a lower average income than the average in the DeSO they belong to uncovered that in 53 % of these cases the average age of the owners was higher than the pension age of 65. A reasonable explanation could be that the pension income usually is lower in Sweden than the salaries of professional workers, but that the retired people living in a single-family house have had time to pay off all, or a big share, of their mortgage loans, as compared to younger people that bought the house more recently. Retired people with a solar energy system might thereby have a better economic situation than their income indicates. This hypothesis is strengthened by the long residence times for households with solar energy systems in Table V, and that the correlation coefficient for *#PV* and average economical standard is stronger than for *#PV* and average income in both Fig. 3, Fig. 4 and Fig. 5 (even if the correlation of these two factors is weak).

4 DISCUSSION

It should be made clear that in the compilation of the private residential systems set, some assumptions were made that lead to uncertainties in the result of this study. Firstly, the owner of each property was assumed to be responsible for the acquisition of the system, even though no insight in the actual financing of a solar energy system was available. The date of the acquisition of the property was either the registration date in the legal registration, or the change of address. Date of commission of PV systems was available, but not for ST systems, so there was no way of knowing if the current occupant household was the actual household that acquired the ST system. This leads to that we expect larger errors for ST systems in the data set. Some systems were justifiably removed, but those that remained was assumed to represent the owner and installer of the inventoried solar energy systems. So possible errors in the data set range from non-existing information about previous owner and lack of or imprecise data.

It should also be noted that the dataset of this study is substantially smaller compared to several of the studies the result is compared to, which can be several hundred thousand of systems [10,11,14–17,21,27,33]. However, our smaller statistical base is counterweighted by that information about the socioeconomic factors of income, age and sex could be presented on household level.

The first finding in this study was that the concentration of both domestic PV and ST systems per total number of households are higher in 'rural' areas as compared to the 'urban' or 'center' areas in the three municipalities. This conclusion is not unique, as higher penetration of PV in rural areas as compared to densely populated metropolitan areas has also been observed in several other countries, such as Australia [10], Belgium [11], Denmark [36], Germany [13], the Netherlands [17], the UK [18–21,32], US [23,26,27]. However, this is to our knowledge the first study which observes this pattern also for ST. This global pattern is at first sight somewhat incongruous, as factors with a reported positive role in adoption, such as high income and population density, generally are higher in urban and metropolitan areas. In this study, the monthly average income of all 'rural' DeSOs was 27,920 SEK, as compared to 29,459 SEK in the 'center' DeSOs. The general explanation for this contradiction in both this and other studies [10,11,13,19,26,33] is that even if there is a concurrence of high income and population density in cities, many more people live in apartment houses, and hence find it hard or even impossible to install private residential solar energy systems. Another explanation could be that a house in the city is relatively more expensive to buy compared to the income difference, which means that the purchasing power for PV or ST decreases.

In the correlation analysis, a moderate positive correlation (0.36) was found between PV penetration and ST penetration, which increased to an intermediate positive correlation (0.61) when two outlier demographic areas were omitted. This finding might be the most significant result of this study, as interaction between ST and PV system distribution has not been investigated thoroughly so far. This finding strengthens previous documentation that in addition to knowledge about a specific technology, such as PV, familiarity of a similar technology, in this study ST, facilitates higher PV adoption [56] and indicative evidence of passive spill over peer effects between PV and ST in Sweden [29].

Furthermore, it should be noted that relatively many households have installed both ST and PV system, as Table IV illustrates. With the assumption that the ST systems was installed first, which is based on the fact that the deployment of ST in Sweden in general took place a decade prior to the PV roll-out, the percentage of households with a ST system that later also have installed a PV system is 6.7% for all municipalities (5.6% in Falun, 14.3% in Knivsta and 4.3% in Uppvidinge). This could be seen as some kind of super household internal spill over peer effect between PV and ST.

In general, when our complete set of domestic PV and ST systems was divided into municipalities or 'rural', 'urban' or 'center' demographic areas, it was shown that the independent variables' effect on PV and ST deployment varied, and some substantial differences were observed. This finding is in line with [28] that found that socioeconomic profile of PV adopters in one town can be quite different from the profile in a neighbouring town and the overall profile. In addition, it confirms that socioeconomic factors can be contextual within regions and countries [10,15,21,26,28,40,49]. The statistical correlation results, the results on a household level and differences between different demographic areas in this study confirm the general image put forward by [36] that early adopters of PV tend to be men living in rural areas with a higher income and education level than others.

5. CONCLUSION

The spatial adoption of domestic PV systems has in numerous studies been proven to be influenced by socioeconomic factors. Our general conclusion, with regards to economic factors, is that the average economic situation in a Swedish demographic area seem to have a small impact on the deployment of domestic PV and ST systems in that area, but that a strong economic situation of a specific household increases the probability of PV or ST investments.

Furthermore, in line with previous studies in Sweden along with several in other countries, the result in this study shows that males, employed households and people with higher education are more prone to install PV systems. The results are basically the same for the likelihood of ST adoption, which so far only occasionally has been addressed by the scientific literature. Regarding age as a factor, the cautious conclusion is that people of age 45–64 seem to be more likely to install solar energy systems than people belonging to both younger and older age groups in Sweden.

This study is also the first of its kind to show that there seems to exist a statistical spatial correlation between solar PV and ST adoption, which can indicate that familiarity of the ST technology in an area can have a passive spill over peer effect on PV adoption.

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