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Should energy efficiency subsidies be tied into housing prices?

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Abstract

Heat pumps are a key technology for improving energy efficiency as they can significantly reduce energy costs and emissions. Given the significant role of heat pumps in carbon neutrality pathways, and pressure for related national energy efficiency programs, it is important to examine economic profitability of heat pump investments and their relative environmental and social benefits. This paper aims to answer the following main research question: are areas with lower housing prices and income less likely to invest into energy efficiency? The paper finds that in Finland heat pumps are already very profitable and converting buildings' heating systems into heat pumps creates major environmental and economic benefits for the residents. The cost of heating and heat pump investment costs does not vary between locations whereas housing prices, rents and income do. Neighborhoods with lower housing prices have less motivation and capability to invest into heat pumps. Urban areas with positive housing price development, higher income and better financing options will likely invest into energy efficiency without subsidies. Potential subsidies should be allocated into areas with lower housing prices, because emissions are evenly distributed, and lower income areas pay relatively more for energy. Energy efficiency subsidies could be tied into housing prices or more specifically into property tax, which is universally collected in most countries. Property tax could be used to guide energy efficiency investments into locations where they would not be carried out otherwise. For areas that do not need subsidies, this paper recommends that awareness should be increased, because the economic and carbon emission reduction potential of energy efficiency measures is still not well understood.

1. Introduction

Global energy-related emissions produce over 80% of CO_2 emissions [1] and approximately 75% of our energy is consumed in cities [2]. Transition to low carbon energy system is the single most important climate challenge to overcome, and solving it requires extensive private investment. It has been estimated that on average annual global low-carbon energy investments of US$3, 400 billion are required until 2050 to meet the 1.5 °C global warming scenario [3]. Nearly a quarter of these investments is subjected to demand-side energy efficiency. One of the key technologies in demand side energy efficiency is heat pumps that can significantly reduce heating costs and emissions of the built environment [4]. International Energy Agency (IEA) [5] has estimated that heat pump installations should triple by 2030 to meet carbon neutrality targets.

Heat pumps uses one unit of electricity to draw multiple units of energy from surrounding air, ground or water, to which it has been originally stored by solar irradiation [6]. As heat pump prices have been decreasing and fossil fuel prices increasing, adoption of heat pumps has increased, especially in the colder climate countries [5]. Even though heat pumps are already competitive and profitable investments [7], high up-front capital expenditure (capex) remains a challenge. Reducing these up-front costs with investment grants and subsidies are often the focus of national energy aid programs [8]. For example, recently Finnish government introduced an energy efficiency subsidy program for residential buildings with a budget of 100 MEUR for years 2020–2022 [9]. The investment aid is granted if certain targets are met, and heat pumps are one of the most cost-efficient ways to meet these targets. Subsequently it has been reported that popularity of heat pumps has already depleted the limited budget as well as backlogged the whole grant process. When the policy was announced, Finnish heat pump federation questioned its necessity, because it could cause market disturbance where investments are postponed until subsidies are available. This phenomenon has also been noticed in academia [10, 11].

Given the significant role of heat pumps in carbon neutrality pathways, and pressure for related national energy efficiency programs, it is important to examine whether and how should heat pump investments be subsidized. To understand this research setting, some real estate economics viewpoints should be given attention. Property owners have the motivation to decrease energy costs that can form up to third of building's operating expenses [12]. However, energy costs do not correlate with real estate values and rents nor with residents' income, as unit price of energy is the same for everyone within a larger region. On this basis, it is of interest to analyze the relationships between heating costs, housing expenses, heat pump capital expenditures and residents' income in different neighborhoods. The aim of this paper is to answer the following main research question: are neighborhoods with lower housing prices less likely to invest into energy efficiency? The paper provides insight on economic profitability of heat pump investments as well as their relative environmental and social benefits.

The results present that in Finland neighborhoods with lower housing prices have less motivation (capex represents higher share of housing prices as well as uncertain expectations of housing price development) and capability (capex represents higher share of available income and worse financing available to cover the investment) to invest into heat pumps. Meanwhile, residents in these neighborhoods have largest benefit from decreased heating expenses, because their share of housing expenses and income is much higher. Furthermore, in past heat pumps have been installed in locations where heat pump capex share of housing prices or income is lower. Since heating emissions per unit of energy are evenly distributed, the most sustainable way to subsidize energy efficiency investments is to understand the underlying housing market dynamics and subsidize locations with lower housing pricing.

2. Methodology and data

This study approaches the research problem by constructing a detailed energy and economic model that contains all buildings of eight large cities in Finland.

2.1. Building data

Building data was acquired for the cities of Helsinki, Espoo, Vantaa, Tampere, Oulu, Turku, Kuopio and Lahti [13]. The first three comprises 1.19 million population Helsinki Metropolitan Area (HMA) and all having a population of 2.07 million. The building data includes information, such as address, building type, floor area, construction year and heating type. Data not including area, construction year and heating type were omitted, as well as buildings with a size less than 100 sqm. This cleaned dataset included a total of 188 k buildings and served as foundation to which the following data and calculus were connected.

2.2. Current heating consumption, costs and emissions

Building type and construction year defines average heating and electricity consumption of buildings [14, 15]. In this study, consumption profiles were created for apartment buildings and (semi-)detached houses constructed in nine different decades (from -1930 to 2010-). The profiles were created for both heating and electricity (for non-heating purposes) based on hourly resolution consumption data of nearly 600 buildings in Helsinki [16]. This data was enriched by multiple research papers and reports focusing on energy consumption in Finland [e.g. 17, 18]. The end result was two matrixes with the size of $27 \times 35\,064$ (27 profiles with hours of years 2016–2019), where rows represent building type plus construction decade and columns hourly consumption per floor area (kWh sqm^{-1}) for the location (outdoor temperature) of HMA. To use the heat consumption profiles for other cities in Finland, a four-order polynomial regression was conducted for the profiles using hourly outside temperature of HMA as variable for the given period (heat demand strongly correlates (>0.93) with outdoor temperature. The R^2-values were between 0.90 and 0.94 for the 27 profiles (see appendix for details). The defined parameters allowed to simulate hourly heat demand based only on outside temperature in degrees centigrade (λ). For household electricity profiles the consumption was assumed to be the same across Finland. The household electricity consumption profiles were required for calculating correctly electricity tariffs are based on the total energy consumption.

Heating costs were calculated based on used heating system. For wood and oil fueled heating systems, energy consumption was multiplied with price of used fuel. Gas is rarely used for residential heating in Finland because of district heating. District heating pricing has two components: monthly or annually priced energy consumption cost and annual peak cost, which is based on maximum peak heat demand of the year. Electricity-based heating systems (heat pumps and electricity heating) have three main components: energy cost, distribution cost and electricity tax. The energy can be purchased from any retailer, but the distribution costs are tariffs from the local naturally monopolized distribution network. The distribution costs consist of monthly peak power costs and energy costs. There are nearly 230 district heating networks and nearly 80 electricity

Table 1. Key descriptives of input data.

Group	Parameter	Value	Reference
Heating Costs (mean of all buildings, incl. 24% VAT)	Wood (fuel cost)	81 € MWh^{-1}	[19]
	Oil (fuel cost)	105 € MWh^{-1}	[20]
	District heating (energy + peak costs)	Espoo 86 € MWh^{-1}	[21]
		Helsinki 86 € MWh^{-1}	[22]
		Kuopio 78 € MWh^{-1}	[23]
		Lahti 83 € MWh^{-1}	[24]
		Oulu 70 € MWh^{-1}	[25]
		Tampere 82 € MWh^{-1}	[26]
		Turku 91 € MWh^{-1}	[27]
		Vantaa 83 € MWh^{-1}	[28]
	Electricity (Nordpool spot + local distribution network + electricity tax)	Espoo 116 € MWh^{-1}	[29]
		Helsinki 117 € MWh^{-1}	[30]
		Kuopio 112 € MWh^{-1}	[31]
		Lahti 126 € MWh^{-1}	[32]
		Oulu 117 € MWh^{-1}	[33]
		Tampere 116 € MWh^{-1}	[34]
		Turku 109 € MWh^{-1}	[35]
		Vantaa 120 € MWh^{-1}	[36]
		Nordpool Spot	[37]
Heating emission factors	Wood	504 $kgCO_2$ MWh^{-1}	[38]
	Oil	292 $kgCO_2$ MWh^{-1}	
	District heating	Espoo 214 $kgCO_2$ MWh^{-1}	[21]
		Helsinki 198 $kgCO_2$ MWh^{-1}	[22]
		Kuopio 117 $kgCO_2$ MWh^{-1}	[23]
		Lahti 175 $kgCO_2$ MWh^{-1}	[24]
		Oulu 218 $kgCO_2$ MWh^{-1}	[25]
		Tampere 177 $kgCO_2$ MWh^{-1}	[26]
		Turku 144 $kgCO_2$ MWh^{-1}	[27]
		Vantaa 177 $kgCO_2$ MWh^{-1}	[28]
	Electricity (national grid)	81 $kgCO_2$ MWh^{-1}	[39]
Heat pump investment specifications (mean of all buildings, incl. 24% VAT) and housing loans specification	Capex	AASHP 394 € kW^{-1}	[40]
		AWSHP 1217 € kW^{-1}	[41]
		GSHP 1782 € kW^{-1}	[42]
			[43]
			[44]
			[45]
			[46]
			[47]
			[48]
			[49]
			[50]
	Opex	6.2 € kW^{-1} a^{-1}	[7]
	Lifecycle	30 a	[7]
	Energy price growth	2.0% p.a. (real)	[43]
	Housing loan maturity	25 a	[44]
	Housing loan interest	1.5% p.a (real)	

distribution networks in Finland, with many of them having their own pricing details. All pricing details have been accounted in the calculus and their details can be found through the references, which are listed in table 1 that presents all key input data used in this study.

Heating emissions are calculated by multiplying energy consumption with relevant CO_2 emission coefficients. Many district heating companies use combined heat and power plants for heat production. Their reported emission coefficients are calculated with benefit allocation method, where emissions are allocated for all produced energy. For the electricity system, hourly resolution data of emissions per consumed electricity in Finland is used.

2.3. Heat pumps energy efficiency and its implication to energy consumption

Three main types of heat pumps were modeled: air-to-air (AASHP), air-to-water (AWSHP) and ground-to-water (GSHP). AASHPs are used in buildings that do not have water circulation for space heating, whereas AWSHP and GSHP are used for buildings that have water circulation. The former two draws energy from surrounding air and the latter from ground, usually from 200 to 300 meters deep drill wells [41]. Heat pump efficiency (i.e. how many units of electricity is required for unit of heat) is a function of temperature difference [45]: input being temperature of outside air or ground (average of 5 °C in Finland [46]), and output being temperature required for space heating or hot water heating, which requires temperature of 58 °C due to legionellae bacteria.

For AASHP, output space heating temperature is the indoor temperature required (21 °C) because it circulates heat directly into indoor air. Unlike AWSHP and GSHP that delivers heating energy into water, AASHP cannot be used for heating hot water. AASHP cannot cover all heating requirements, as it has to heat up hot water directly with electricity. The space heating output temperature for AWSHP and GSHP depends on building's thermal characteristics and outside temperature [6]. Finnish Energy Federation has recommended temperatures (as a function of outside temperature) for different building types and construction years, ranging from 35 °C to 80 °C as a maximum temperature [47]. The building database was used to calculate hourly output temperature for every building based on these two characteristics.

Heat pump energy efficiency also depends on manufacturer. Manufacturer data was collected to understand heat pump coefficient of performance (COP) in different temperatures [48]. A two-order polynomial regression with temperature difference can be used to define a function for measuring COP [6, 45]. Figure 1 presents manufacturer data and the regression coefficients that were used to calculate hourly resolution heat pump energy efficiency (COP) for all of the buildings based on their individual temperature differences. This calculus also included the maximum and minimum temperature levels where the heat pumps can operate. Most ASHP or AWSHP heat pumps had the limit of −20 °C or −25 °C as the minimum outside air temperature. For AWSHP and GSHP, the respective maximum output temperatures were 60 °C and 65 °C. If the water circulation system required a higher temperature than this, it had to be covered with direct electricity heating with energy efficiency of 1:1. Often the amount of these hours per year are rather low, which leads to optimal sizing of a heat pump: the maximum power of the heat pump is not necessary the same as the maximum heating power required, as the peak hours can be covered with direct electricity boilers that have much lower relative investment costs. Nevertheless, heat pumps were sized to cover as much as possible of the required heat, but not oversizing. Depending on the construction year and building type the sizing of heat pumps was between 75% and 100% (maximum power of heat pump per maximum heating required). This sizing depends on the required output temperature. For example, newer buildings can cover their heat demand with high efficiencies even in very low temperatures because their output temperature need is lower.

Finally, heating consumption with heat pumps were calculated by dividing, on hourly resolution, the original heat consumption with the calculated COP of heat pump. These new consumption profiles were then used to calculate new heating costs and emissions using the above principles for electricity-based heating systems.

2.4. Heat pump capex

Four main categories were used to calculate heat pump capex: (a) heat pump unit, (b) installation and ancillary costs, (c) drilling for ground-source heat pumps, (d) planning and supervision and (e) electricity connection upgrade. The heat pump unit costs were collected together with the manufacturer data [40, 48], and an exponential function with peak power as variable was used to calculate pricing as a function of power, because unit price for higher sized units is less expensive (see figure 1). The installation and ancillary costs were approximately twice as much as the heat pump unit costs, based on the energy consumption of the building [40–42]. It is mentioned that, especially in apartment buildings, current Heating, Ventilation, and Air Conditioning (HVAC) systems and building's technical layout can have high impact on these costs. The drilling was estimated based on the energy consumption of the building: one meter of a borehole can produce approximately 100 kWh of energy per annum in southern Finland [41, 49]. This was used to calculate the total required drilling depth in meters that is then multiplied by average drilling price [40]. The borehole production per meter was assumed to decrease by 5% in Middle Finland and in Northern Finland due to lower ground temperatures [46]. Planning and supervision was 5% of total costs [41]. The fifth category was based on the local electricity distribution network tariffs [29–36].

2.5. Housing and demographic data

Statistics Finland updates housing price statistics for apartment buildings and (semi-)detached houses on postal code level [50]. The data is in the form of mean price (€ sqm^{-1}), and available from 2010 onwards. The most recent data for the year 2020 data was available for 225 postal codes. Housing rents were collected from a service operated by the Housing Finance and Development Centre of Finland [50]. The service included mean rent (€ sqm^{-1} a^{-1}) on postal code level for the 225 postal codes. This data is not separated into apartments and (semi-) detached housing. This data was joined to the building database on a postal code level.

Statistics Finland also gathers mean floor area per resident on a city level, which was used to calculate total residents per building. Statistics Finland also gathers the ratio between working adults (18–65 years old) [52] and all residents, and median income per

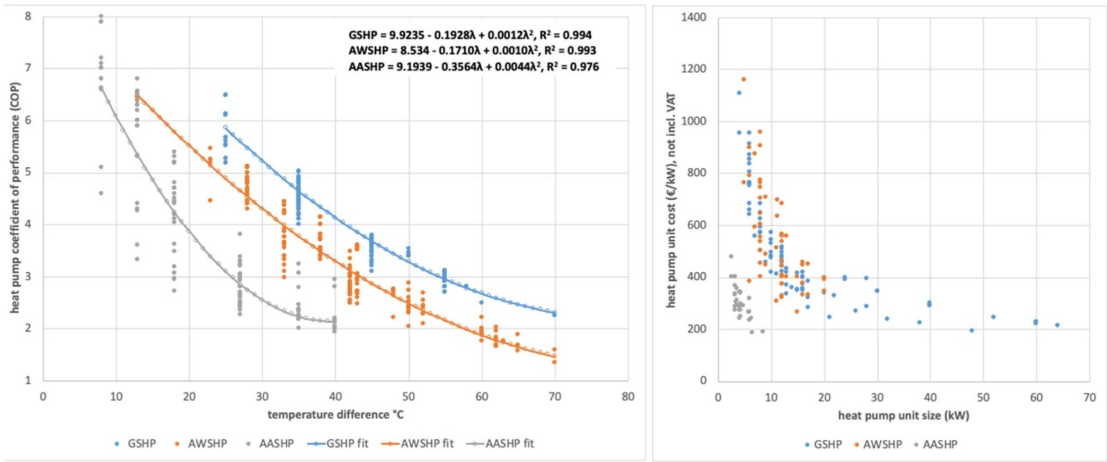

Figure 1. Different types of heat pumps' energy efficiencies in temperature differences and heat pump unit costs.

working adult on a postal code level [53]. This ratio and median income was joined to the building database via postal code. Finally, the combined dataset allowed to compute housing price, housing rent, number of residents and adults, and median income for all of the buildings.

2.6. Calculating economic returns

This study uses three widely used parameters to assess the economic return of the investments: payback period (PP), net present value (NPV) and internal rate of return (IRR). PP is a very simple method to calculate how attractive an investment is, and it does not take into account the time value of money. NPV and IRR are more sophisticated methods that takes into account the time value of money and are often used by professionals. The following equations are used for PP, NPV and IRR:

$$\mathrm{PP} = \frac{\mathrm{CAPEX}}{\mathrm{CF}_1}$$

$$\mathrm{NPV} = \sum_{i=1}^{n} \frac{\mathrm{CF}_i}{(1+r)^i} - \mathrm{CAPEX},$$

$$0 = \sum_{i=1}^{n} \frac{\mathrm{CF}_i}{(1+\mathrm{IRR})^i}$$

where n is the total number of periods, i is number of period, CF is cash flow for the period, and r is the used discount rate for the period. The discount rate is the rate of return that the investor expects from the investment. If NPV is positive, investment should be carried out. IRR represents annual rate of return for the investment's lifecycle where the NPV is zero. IRR is compared to the investor's discount rate, i.e. investments with an IRR that is larger than the investor's discount rate should be undertaken. NPV and IRR can be both used together or separately. The information they provide can supplement each other, as NPV measures the absolute impact and IRR relative impact of an investment's performance.

In this study, CF is the annual savings created by the heat pump investment (current heating expenses—new heating expenses), N is 30 years (lifecycle of heat pump), and the discount rate is the net rental income (rent—opex) per housing price, as calculated in real estate economics [54]. The energy costs are expected to increase by 2.0% annually (real), based on historical data [43]. Current and new heating costs includes annual operating expenses. Additionally, for heat pumps, it is assumed that at year 15 replacements to the heat pump system have to be made (30% of the original capex) [7].

2.7. Validating the energy model against real heating consumption of cities

The constructed energy model also includes energy profiles and consumption for different types of commercial buildings. Even though this data is not used in this study, it was used to validate the model's performance against real energy consumption. District heating companies, which often have significant market shares (up to 90%) in larger Finnish cities, publishes their annual numbers for total heating delivered. These numbers were compared to the aggregated numbers of the model. In 2019, the district heating companies in these eight cities delivered a total of 18 845 GWh whereas the model calculated a delivery of 19 049 GWh, a difference of 1.1%. Table 2 presents the differences in all of the cities. The differences are quite small in all of the cities except Kuopio, which has a large difference. Meta-analysis of the building stock compared to other cities does not reveal the reason for this large difference.

3. Results

Table 3 presents some aggregated results of final model that includes 110 k residential buildings in 225

Table 2. Model difference vs real heat consumption (all buildings with district heating).

City	Model (GWh)	Real (GWh)	Difference (GWh $\%^{-1}$)	
Espoo	1938	1950	−12	−0.6%
Helsinki	6510	6556	−46	−0.7%
Kuopio	1292	946	346	26.8%
Lahti	1348	1280	68	5.0%
Oulu	2104	2259	−155	−7.4%
Tampere	2264	2250	14	0.6%
Turku	1874	1897	−23	−1.2%
Vantaa	1719	1707	12	0.7%
All	19 049	18 845	204	1.1%

different postal code areas in eight cities. 2019 data is used for all results.

The average heating cost share of rent is 9.4% and heat pumps could decrease it to 3.8%, or to 6.3% including loan amortization. On average, a resident saves 393 € on heating expenses (213 € including amortization) and reduces CO_2 of emissions by 1213 kg (−86%). This would require an average investment of 3782 € per resident with a PP of 10.1 years. Conversion into heat pumps creates 4545 € of value per resident (NPV) and IRR of 13.6%. The average IRR is higher than the mean real estate discount rate of all of the postal codes (3.8%). The results also imply that, on average, HP investments are profitable in all of the postal codes. Sensitivity analysis was also carried to test how a shorter lifecycle affects the economical parameters. For a lifecycle of 25 years, the average NPV per resident is 3635 € and IRR 13.1%. For a lifecycle of 20 years, the respective numbers are 2395 € and 11.7%.

To understand the difference between locations, housing prices, rents and median income of residents are analyzed on a postal code basis. Figure 2 presents housing prices for years 2020 and 2010 as well as heat pump capex and its share of current housing prices. The dashed line part of the 2010 housing prices is estimated from the adjacent postal codes as the historical prices were not available for all of the locations (106 postal codes).

HP capex has a mean value of 98 € sqm^{-1} and a standard deviation of 21 € sqm^{-1}. The 2020 housing price has a mean of 3366 € sqm^{-1} with a standard deviation of 1640 € sqm^{-1}. Capex has low variation compared to housing prices. For the first half of residents (790 k residents), HP capex share per housing price varies between 0.8% and 3.6% (mean 2.1%) and for the second half between 1.8% and 11.4% (mean 5.1%). For the first decile of residents, the mean is 1.3% and for the last decile the mean is 8.0%. Positive housing price development has focused on certain cities and areas, with especially heavy focus in some key urban areas. Postal codes on the left are more likely invest into heat pumps as the relative investment cost is lower and the housing price development positive. Additionally, these two factors increase the availability and cost of long-term housing loans that can be used for these kinds of investments. This can further increase the motivation to invest into heat pumps. Figure 3 presents similar analysis from the perspective of housing rents.

Current heating costs (HP heating costs in brackets) has a mean value of 18 € sqm^{-1} a^{-1} (8 € sqm^{-1} a^{-1}) and a standard deviation of 2 € sqm^{-1} a^{-1} (1 € sqm^{-1} a^{-1}). The 2020 housing rents has a mean of 183 € sqm^{-1} a^{-1} with a standard deviation of 38 € sqm^{-1} a^{-1}. Heating costs also has a low variation compared to rents. For the first half of residents, heating costs per rent varies between 5.1% and 13.8% (mean 8.5%) and for the second half between 6.9% and 23.8% (mean 11.8%). For the first decile of residents, the mean is 6.8% and for the last decile the mean is 14.8%. Installation of a HP system, which approximately halves the heating costs, has a much higher relative impact on housing expenses on areas with lower rents. As housing prices and rents are strongly correlated (0.86), areas on the right are less likely to investment into a HP than the areas on left, even though the relative impact on housing expenses would be much higher. In figure 4, income is added to the analysis. Since median income is calculated only for adults, their income has to cover all residents (including children) costs.

Rent per income has high variation, but the trend remains quite linear throughout the postal codes, i.e. rent per income does not correlate with housing prices (−0.13). However, there is a clear trend that income is lower for areas with lower housing prices (correlation of 0.51). On the contrary, heat pump investment capex share of income is much higher for areas with lower housing prices (−0.60). Also heating costs share of income has a negative correlation with median income (−0.68). For the first half of residents, capex share of income varies between 7.1% and 30.3% (mean 15.8%) and for the second half between 7.9% and 39.7% (mean 24.3%). For the first decile of residents, the mean is 14.0% and for the last decile the mean is 31.2%. Areas on the right less likely invest into heat pumps as capex share on

Table 3. Economic and environmental potential of heat pumps per resident (note: for majority of electricity heated buildings, the modeled heat pump is AASHP, because electricity heating is often air-circulated).

							Current heating system					Current converted to HP heating system (GSHP not converted)						
Building type	Heating fuel	Residents	Floor area (sqm)	Value (m€)	Rent (m€ a^{-1})	OPEX (m€ a^{-1})	Heat cost (m€ a^{-1})	Heat consumption (GWh a^{-1})	Heat emissions (t $kgCO_2$ a^{-1})	Heat cost per resident (€ a^{-1})	Heat emissions per resident ($kgCO_2$ a^{-1})	Heat cost per resident (€ a^{-1})	Heat emissions per resident ($kgCO_2$ a^{-1})	HP capex per resident (€)	HP loan annuity per resident (€ a^{-1})	Payback period (a)	NPV per resident (€)	Internal rate of return (%)
Apartment buildings	DH	1030 471	38 777 372	148 049	7681	2280	663	8222	1525 121	644	1480	256	188	3967	190	11.0	3960	9.9%
	GSHP	7547	302 963	921	55	18	2	60	1355	237	180							
	Wood	848	34 773	145	7	2	1	7	3544	664	4179	541	380	1182	57	13.6	1462	9.2%
	Electricity	4670	192 423	660	36	11	5	42	3649	1021	781	527	381	1605	77	3.0	9366	40.6%
	Oil	19 881	797 750	2 731	150	47	20	190	55 371	1000	2785	311	228	4802	230	8.3	8945	13.2%
	Total	1063 417	40 105 281	152 507	7927	2358	690	8520	1589 041	649	1494	258	190	3972	191	10.9	4096	10.1%
Detached houses	DH	88 108	3704 789	9 853	607	175	59	722	137 797	673	1564	256	169	5014	241	13.8	2820	7.2%
	GSHP	34 764	1398 584	4 091	236	66	7	213	4457	193	128							
	Wood	8233	351 874	868	55	17	6	78	39 368	769	4782	504	352	2918	140	11.1	2008	10.2%
	Electricity	153 215	6013 676	17 643	1023	284	139	1184	102 528	906	669	472	328	1524	73	3.5	7501	36.6%
	Oil	40 027	1686 862	4 657	279	80	43	402	117 509	1063	2936	347	233	6162	296	9.9	6845	10.7%
	Total	324 347	13 155 785	37 112	2200	620	254	2600	401 658	782	1238	387	265	3407	164	7.9	5795	22.5%
Semi-detached houses	DH	144 873	5729 070	15 999	972	269	86	1065	197 748	590	1365	198	143	3831	184	11.5	3786	9.5%
	GSHP	5460	226 013	645	37	11	1	34	648	159	119							
	Wood	561	23 963	74	4	1	0	5	2304	658	4107	399	288	1451	70	5.1	4087	25.4%
	Electricity	33 901	1331 997	883	223	63	29	249	21 611	842	637	398	284	950	46	2.1	8559	57.8%
	Oil	14 748	567 260	1 668	94	27	12	118	34 344	840	2329	228	165	4120	5	7.7	7681	14.2%
	Total	199 543	7878 303	22 269	1331	370	128	1470	256 655	640	1286	236	170	3347	145	9.5	4935	18.3%
All	Total	1587 307	61 139 369	211 887	11 458	3349	1072	12 590	2247 354	675	1416	282	203	3782	180	10.1	4545	13.6%

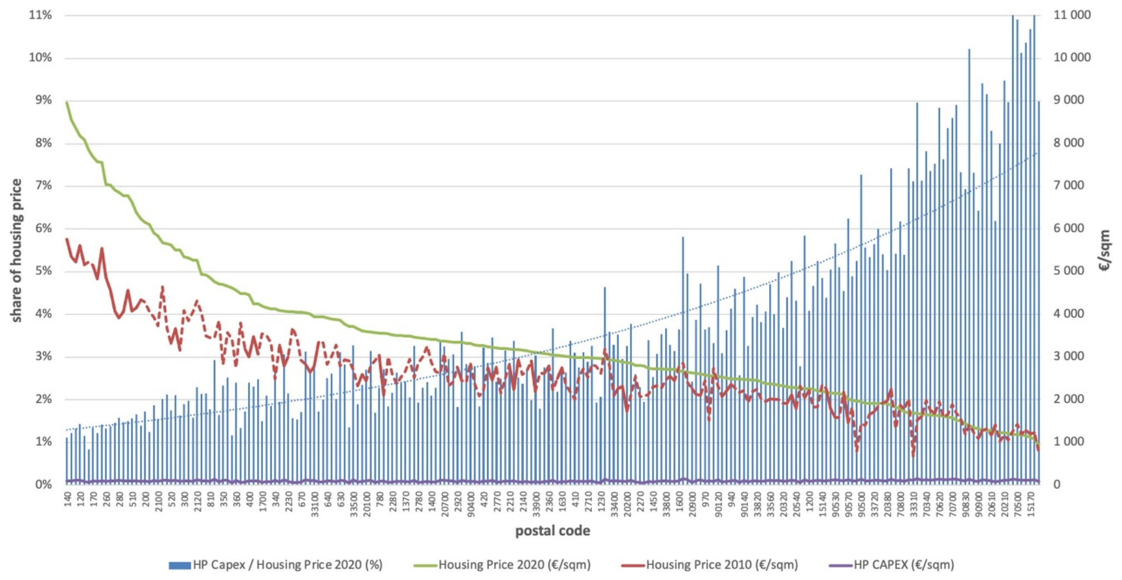

Figure 2. Housing price development and heat pump capex share of current mean housing prices per postal code (sorted by descending housing prices).

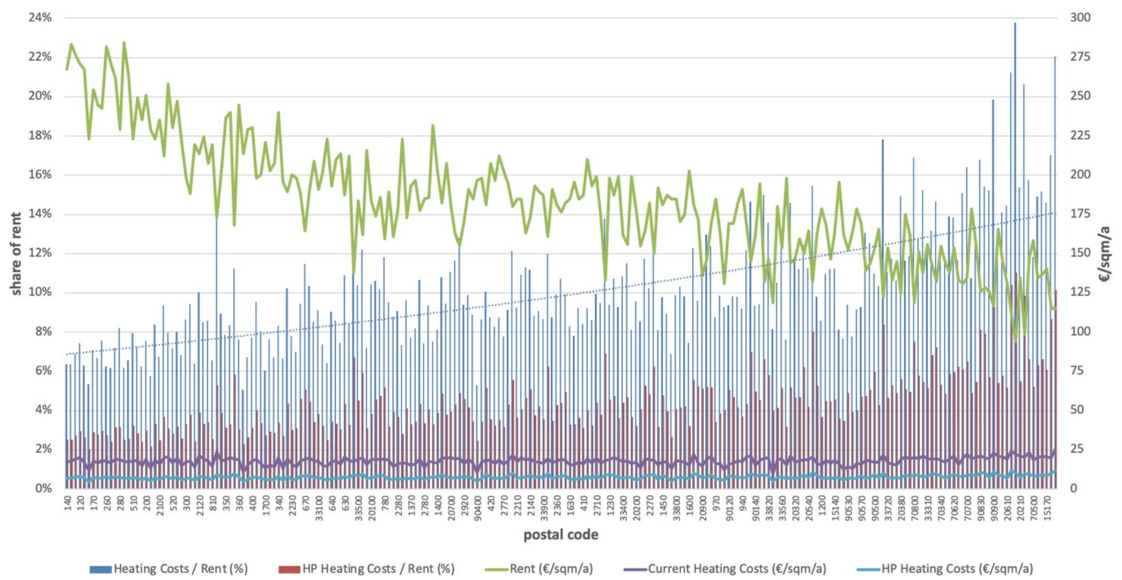

Figure 3. Current heating costs and HP heating costs share of current housing rents per postal code (sorted by descending housing prices).

income is higher, even though the relative impact from lower heating costs to available income is much larger.

Finally, Geographic Information System (GIS) is used to analyze where GSHP systems have been installed in the past in HMA. In figure 5, green dots are GSHP systems and red dots non-GSHP systems with water circulation heating (i.e. could be converted into GSHP or AWSHP). Postal codes with median income have been added as another layer. All layers have been divided into four equal quantiles. It is noted that the large concentration of white dots in the lower middle center are mostly apartments buildings of downtown Helsinki, where district heating has historically delivered almost all of heating.

Most GSHP are in areas where capex share of median income is lower (lighter blue areas). It also seems that s significant share of GSHP is in buildings, where capex share of housing price is lower (lighter green dots). The histograms present that GSHP buildings have lower mean values and are right skewed compared to non-GSHP buildings. Two sample t-test for comparing means confirms that the means differ between the two groups: GSHP systems have been constructed in areas with higher housing prices and higher income. The same statistical result applies for

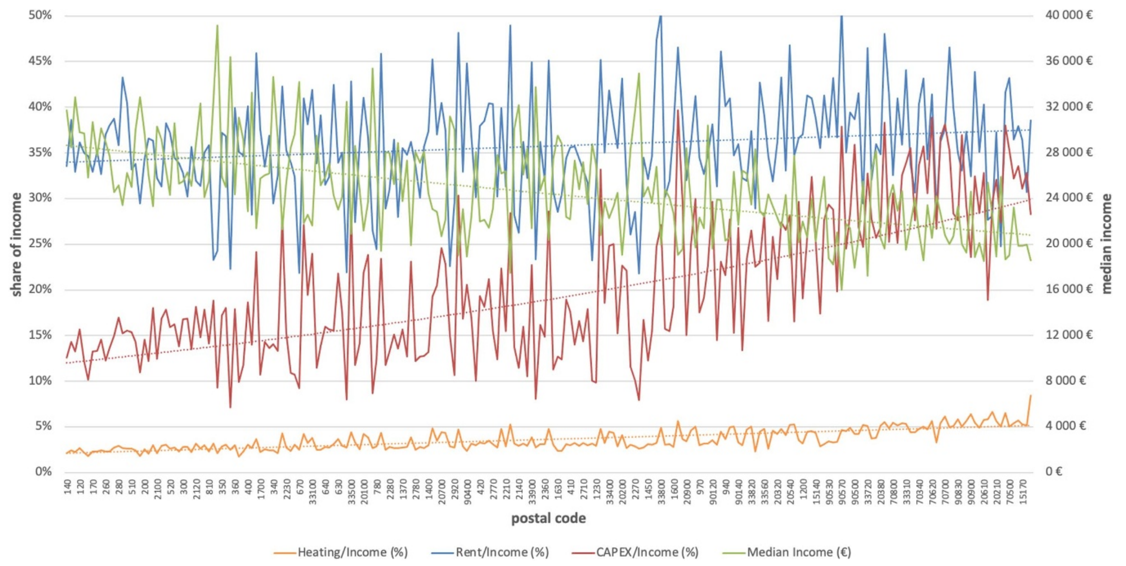

Figure 4. Current heating costs, housing rents, and heat pump capex share of median income per postal code (sorted by descending housing prices).

all of the cities in the dataset: Turku (t-value of 10.675 for capex per housing price), Tampere (13.796), Lahti (8.580), Kuopio (10.716) and Oulu (10.109) with 0.000 p-values.

4. Discussion

Heat pumps have been identified as one of the key technologies for improving energy efficiency as they can significantly reduce energy costs and emissions [5]. Since post COVID-19 green stimulus has a major focus on energy efficiency [55], it is very important that the funds are distributed into targets with highest potential impact following the sustainable development principles. The aim of this paper was to answer the following main research question: are areas with lower housing prices and income less likely to invest into energy efficiency? The paper provides insight on the profitability of heat pump investments as well as their relative benefits in different areas.

The paper finds that in Finland heat pumps are already very profitable in many locations as their returns can be multiple times higher than the underlying real estate returns. Converting buildings' heating systems into heat pumps creates major environmental and economic benefits for the residents. The cost of heating and heat pump capex does not vary between locations whereas housing prices, rents and income do. Neighborhoods with lower housing prices have less motivation (higher share of housing prices and uncertain expectations of housing price development) and capability (investment represents higher share of available income as well as more expensive financing) to invest into heat pumps.

Urban areas with positive housing price development, higher income and better financing options will likely invest into energy efficiency without subsidies. Potential subsidies should be allocated into areas with lower housing prices, because emissions are evenly distributed, and lower income areas pays relatively more for energy. Previous literature has found that better energy efficiency, was it in the form of energy performance ratings [56], rooftop photovoltaics [57] or heat pumps [58] seems to command higher sales prices for housing. This even further highlights the importance of this paper's findings as increased housing prices coupled with the reigning low interest environment further increases market-based demand for these kinds of investments.

The study uses data from Finland, which due to cold temperatures has higher heating energy demand and lower heat pump efficiencies than warmer countries. On the other hand, Finland's relatively clean electricity sector with low electricity pricing increases environmental and economic performance of heat pumps. These factors should be accounted for when comparing detailed results of this paper to other countries and regions. Future research on conducting similar analysis on other countries is suggested. For example, in the US and many European countries natural gas is the dominant form of heating, and its pricing can be significantly lower than electricity.

This paper produces some important insights regarding real estate markets and energy efficiency investments. Energy efficiency subsidies could be tied into housing prices or more specifically into property

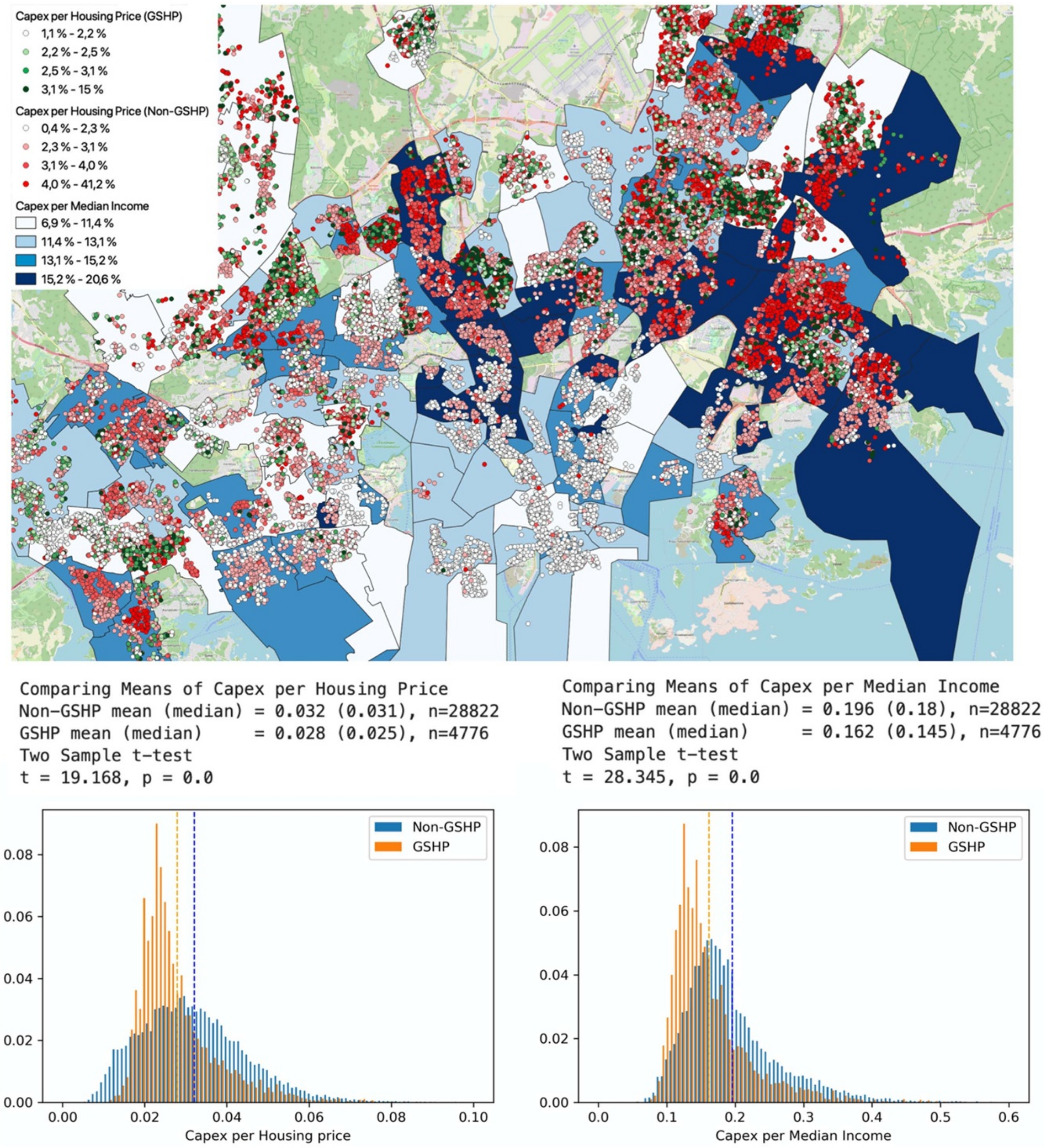

Figure 5. GSHP and non-GSHP locations in Helsinki Metropolitan Area map, histograms for comparing their means per housing price and per median income.

tax, which is universally collected in most countries. Property tax could be used to guide energy efficiency investments into locations where they would not be carried out otherwise. For areas that do not need subsidies, this paper recommends that information should be increased, because the economic and carbon emission reduction potential of energy efficiency measures is still not well understood. This is likely the most efficient use of funds in these areas.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Appendix

Regression parameters for different housing building types through construction decade.

Building type	Construction decade	R^2	Intercept	λ	λ^2	λ^3	λ^4
Apartment building	−1930	0.901	0.022 424 74	−0.001 2543	$-5.840\,98 \times 10^{-6}$	$5.223\,92 \times 10^{-7}$	$2.022\,13 \times 10^{-8}$
Apartment building	1940	0.901	0.025 028 82	−0.0014	$-6.519\,27 \times 10^{-6}$	$5.830\,54 \times 10^{-7}$	$2.256\,96 \times 10^{-8}$
Apartment building	1950	0.901	0.029 742 35	−0.001 6636	$-7.747\,01 \times 10^{-6}$	$6.928\,58 \times 10^{-7}$	$2.681\,99 \times 10^{-8}$
Apartment building	1960	0.901	0.034 9284	−0.001 9537	$-9.097\,82 \times 10^{-6}$	$8.136\,68 \times 10^{-7}$	$3.149\,64 \times 10^{-8}$
Apartment building	1970	0.901	0.031 784 85	−0.001 7779	$-8.279\,02 \times 10^{-6}$	$7.404\,38 \times 10^{-7}$	$2.866\,18 \times 10^{-8}$
Apartment building	1980	0.901	0.026 319 17	−0.001 4695	$-7.099\,42 \times 10^{-6}$	$6.167\,54 \times 10^{-7}$	$2.380\,02 \times 10^{-8}$
Apartment building	1990	0.902	0.026 799 07	−0.001 5007	$-7.271\,39 \times 10^{-6}$	$6.781\,42 \times 10^{-7}$	$2.262\,27 \times 10^{-8}$
Apartment building	2000	0.900	0.023 261 21	−0.001 2948	$-6.405\,02 \times 10^{-6}$	$5.230\,38 \times 10^{-7}$	$2.188\,03 \times 10^{-8}$
Apartment building	2010	0.933	0.017 777 82	−0.001 2043	$-3.206\,13 \times 10^{-6}$	$7.118\,65 \times 10^{-7}$	$1.215\,25 \times 10^{-8}$
Detached house	−1930	0.934	0, 02850142	−0.001 9455	-4.5868×10^{-6}	$1.214\,75 \times 10^{-6}$	$1.656\,22 \times 10^{-8}$
Detached house	1940	0.934	0.032 776 63	−0.002 2373	$-5.274\,82 \times 10^{-6}$	$1.396\,96 \times 10^{-6}$	$1.904\,66 \times 10^{-8}$
Detached house	1950	0.934	0.034 2017	−0.002 3346	$-5.504\,16 \times 10^{-6}$	1.4577×10^{-6}	$1.987\,47 \times 10^{-8}$
Detached house	1960	0.934	0.038 476 91	−0.002 6264	$-6.192\,18 \times 10^{-6}$	$1.639\,91 \times 10^{-6}$	2.2359×10^{-8}
Detached house	1970	0.934	0.034 2017	−0.002 3346	$-5.504\,16 \times 10^{-6}$	1.4577×10^{-6}	$1.987\,47 \times 10^{-8}$
Detached house	1980	0.934	0.028 327 52	−0.001 914	$-5.884\,44 \times 10^{-6}$	$1.175\,72 \times 10^{-6}$	$1.861\,51 \times 10^{-8}$
Detached house	1990	0.902	0.026 775 66	−0.001 5253	$-5.400\,65 \times 10^{-6}$	7.04×10^{-7}	$2.026\,78 \times 10^{-8}$
Detached house	2000	0.939	0.024 724 67	−0.001 5245	$-1.065\,69 \times 10^{-5}$	$9.605\,47 \times 10^{-7}$	$1.663\,57 \times 10^{-8}$
Detached house	2010	0.933	0.017 7927	−0.001 2095	$-3.295\,62 \times 10^{-6}$	7.6475×10^{-7}	$1.043\,51 \times 10^{-8}$
Semi-detached house	−1930	0.915	0.025 598 77	−0.001 1418	$-1.610\,19 \times 10^{-5}$	$3.668\,51 \times 10^{-7}$	$2.913\,77 \times 10^{-8}$
Semi-detached house	1940	0.915	0.029 438 58	−0.001 313	$-1.851\,72 \times 10^{-5}$	$4.218\,79 \times 10^{-7}$	$3.350\,84 \times 10^{-8}$
Semi-detached house	1950	0.915	0.030 718 52	−0.001 3701	$-1.932\,23 \times 10^{-5}$	$4.402\,21 \times 10^{-7}$	$3.496\,53 \times 10^{-8}$
Semi-detached house	1960	0.915	0.033 756 62	−0.001 5056	$-2.123\,33 \times 10^{-5}$	$4.837\,59 \times 10^{-7}$	$3.842\,34 \times 10^{-8}$
Semi-detached house	1970	0.916	0.030 717 49	−0.001 3832	$-1.863\,98 \times 10^{-5}$	$4.814\,02 \times 10^{-7}$	$3.311\,57 \times 10^{-8}$
Semi-detached house	1980	0.935	0.028 337 81	−0.001 9118	-6.2586×10^{-6}	$1.195\,03 \times 10^{-6}$	1.8264×10^{-8}
Semi-detached house	1990	0.902	0.0267 9412	−0.001 5054	-6.8244×10^{-6}	$6.706\,16 \times 10^{-7}$	$2.249\,45 \times 10^{-8}$
Semi-detached house	2000	0.902	0.023 265 04	−0.001 3001	$-6.252\,47 \times 10^{-6}$	$5.541\,09 \times 10^{-7}$	$2.073\,56 \times 10^{-8}$
Semi-detached house	2010	0.935	0.017 792 07	−0.001 2068	$-3.412\,52 \times 10^{-6}$	$7.513\,43 \times 10^{-7}$	$1.101\,04 \times 10^{-8}$

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