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Adoption of Renewable Home Heating Systems: An Agent-Based Model of Heat Pump Systems in Ireland*

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Abstract

Concern about climate change and dependence on fossil fuels is inducing countries to develop and deploy renewable energy technologies. Heat pump systems, which extract heat either from the air, water, or ground sources, are among the viable options for space heating and domestic hot water production in the residential sector. In this paper, we develop an agent-based model to analyze the adoption process of heat pump systems and the underlying diffusion factors. Uniquely, we use a recent nationally representative Irish household survey data to derive parameters for decision rules for technology adoption in the model. In this research, we explore how financial aspects, psychological factors and social networks influence the adoption and diffusion of heat pump systems. We also discuss how individual household socio-demographic characteristics, building characteristics, geographical location of household and policy incentives affect the adoption process. The research should be of interest to policymakers, as we use the model to test the impact of various policies on technology adoption rates.

Keywords: Agent-based model; heat pump systems; energy economics; renewable energy technology adoption; Ireland.

JEL codes: D12, D91, Q41, Q68, Q28

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1. Introduction

The use of conventional fuels such as oil, gas, and coal for various end-uses generates a significant amount of greenhouse gases that lead to climate change and health problems (IPCC, 2007). The residential sector, more specifically residential space and water heating, accounts for a significant share of final energy consumption and associated CO_2 emissions in many countries. For example, the Irish residential sector accounts for 23% of final energy consumption and 25% of energy-related CO_2 emissions in 2016 in Ireland (SEAI, 2018).[1] Of this, a large share of space and water heating comes from the direct use of fossil fuels such as oil, solid fuels and gas (SEAI, 2018).[2] One strategy to curb the use of conventional fuels and the associated greenhouse gases emission is to facilitate the adoption and deployment of renewable energy-using heating technologies.

Among the viable renewable energy technologies, heat pump systems that extract heat either from the air, water, or ground sources offer the potential to provide space and water heating. Compared to carbon-intensive heating systems, heat pump systems are more efficient and environmentally friendly (Bakirci, 2010; Self et al., 2013). Although heat pump systems provide a wide range of social and private benefits, the current levels of adoption are low in many countries, albeit they are growing (European Environment Agency, 2018). This is due to higher upfront costs than comparable fossil fuel heating systems and other barriers related to physical constraints such as building and space requirements for the technology (Karytsas and Choropanitis, 2017). An important additional set of barriers include a lack of awareness and trust in the technology, the perceived risk, and a lack of informed suppliers (Karytsas and Choropanitis, 2017; Michelsen and Madlener, 2016).

Financial incentives have been offered to consumers in order to encourage uptake; however, the adoption of heat pump systems is a complex process that goes beyond financial factors (Kiesling et al., 2012). Among others, it involves environmental attitudes, the level of comfort before and after installation, attitude towards the technology and the hassle associated with the installation (see, e.g., Michelsen and Madlener, 2012, 2016; Yoon et al., 2015; Snape et al.,

[1] The transport sector accounts 42% of the final energy consumption, industry for 21%, services for 12% and agriculture for 2%. Similarly, 37% of the energy-related CO_2 emissions come from the transport sector, 25% from the industry, 13% from services and 2% from agriculture sector.

[2] 2% are for cooking, 17% for lighting and appliances and the 1% is for other end-uses.

2015). It is, therefore, crucial to take these additional factors into account in modeling the uptake of heat pump systems.

In this paper, we develop an agent-based model to analyze the adoption process of heat pump systems and the underlying diffusion factors. An agent-based model is a computational simulation in which autonomous decision-makers called agents with a specific set of characteristics interact with each other and with their environment according to predefined rules, to explain aggregate behavior that emerges from these interactions (Wilensky and Rand, 2015). Unlike the traditional, more aggregated models, an agent-based model enables us to account for individual heterogeneity and design for what-if type of questions (Kiesling et al., 2012; Zhang and Vorobeychik, 2017). In our model, agents represent households who could potentially install a heat pump system in their home. To evaluate household adoption decision of heat pump system, we consider financial aspects, psychological factors, and the influence of social networks.

In the financial decision making, our model compares the agent's annual heating bill of the existing heating system with the annualized capital cost and running cost of a heat pump system. The psychological factors account for an agent's attitude, the social norm, perceived behavioral control, and intention to install a heat pump system, which are constructed based on the theory of planned behavior (Ajzen, 1991). The social network factor captures the influence of other agents within the agent's social interaction that have already installed a heat pump system at their home. Household utility from installing a heat pump system is then formulated as a function of the three factors. A potential adopter decides to install a heat pump system when the sum of the weighted utilities from the three factors exceeds a certain threshold level.

Uniquely, we use a recent nationally representative Irish household survey data to derive parameters for decision rules based on empirical data. We also utilize historical data on heat pump uptake from Finland and Sweden to calibrate the model parameters. Our baseline model predicts that approximately 260, 000 Irish households will install a heat pump at their home in 2030. The result also shows that homeowners, households in Dublin County and households with higher education and a larger number of bedrooms are more likely to adopt a heat pump. The study sheds light on the fact that, in addition to financial aspects, the adoption of renewable energy technologies like heat pump systems involves the influence of behavioral factors and social networks. The findings of the study can provide important information to policymakers on the factors that influence the adoption process and how policy incentives such as available grants might be supplemented with other more targeted policies to deliver more effective outcomes for the adoption process.

The remainder of the paper is organized as follows. Section two provides a review of the literature. Section three describes the materials and the agent-based model. Section four presents and discusses the simulation results. Finally, section five provides a conclusion.

2. Literature Review

Adoption and diffusion of technology have been studied using different approaches. Traditionally, researchers use diffusion of innovation theory (Rogers, 2003) to understand how innovation – ideas, practices and technologies that are perceived as new by individuals – spread throughout a social system over time. The diffusion of innovation theory dates back at least to the empirical work by Ryan and Gross (1943) who investigate the diffusion of hybrid seed corn in Iowa communities. Since then a vast body of literature has investigated the diffusion of new products. The diffusion of innovation theory is based on the model developed by Bass (1969) that describes the diffusion of innovation as a contagious process that is initiated by external forces (mass communication and advertising) and propelled by internal forces (words-of-mouth). It assumes that the cumulative adoption follows an S-shaped curve over time.

The Bass Model is an aggregate, top-down model, which provides an empirical generalization based on differential equations. Later the model was extended to incorporate the influence of factors such as prices, different forms of advertising, or specific market characteristics and is referred to as the Generalized Bass Model (Mahajan et al., 1990). However, the traditional aggregate model developed by Bass (1969) neglects individual heterogeneity and the complex dynamics of the social process that shape the diffusion and it assumes a fully connected and homogenous network (Kiesling et al., 2012; Zhang and Vorobeychik, 2017). In addition, it is not designed for what-if type questions; it simply uses historical data to forecast future uptake (Kiesling et al., 2012; Zhang and Vorobeychik, 2017).

An agent-based model has gained popularity in its ability to model complex emergent phenomena and overcome the shortcomings of aggregate diffusion models. An agent-based model is a computational simulation in which autonomous decision-makers called agents with a specific set of characteristics interact with each other and with their environment according to predefined rules and it is from these interactions that aggregate patterns emerge (Wilensky and Rand, 2015). This is a bottom-up, micro-level model, which does not impose any functional form and assumptions, allows capturing a complex structure and dynamic interactions (Kiesling et al., 2012). Thus, the agent-based model provides a suitable framework to explore how various factors such as individual agent's characteristics and social networks affect diffusion of innovation and helps to evaluate different policy scenarios.

Agent-based model has been applied in various domains; see Kiesling et al. (2012) and Zhang and Vorobeychik (2017) for an up-to-date and comprehensive review. Recent studies have employed an agent-based model to model the adoption of renewable energy technologies such as solar photovoltaic (Palmer et al., 2015) and electric vehicles (see, e.g., McCoy and Lyons, 2014; Elkamel et al., 2016). There are also studies that use an agent-based model to model diffusion of heating systems including heat pumps. For instance, Sopha et al. (2013) use an agent-based model coupled with empirical survey data for simulating heating system adoption in Norway. The study indicates that the functional reliability of wood-pellet heating and price volatility are important variables. Snape et al. (2015) develop an agent-based model to examine the UK Renewable Heat Incentive on the uptake of heat pumps. In addition to economic factors, their model considers non-financial factors such as hassle and social factors and finds that uptake is sensitive to installation hassle.

Other previous studies have documented the factors that facilitate and hinder the adoption of renewable heating systems including heat pumps using empirical data. For example, Mahapatra and Gustavsson (2008) find economic aspects and functional reliability the most significant factors for considering a new heating system among Swedish households. The study shows that installers and interpersonal sources are the main communication channels for information on heating systems. Karytsas and Choropanitis (2017) find a lack of awareness of the technology and its benefits, high upfront cost and installation process a significant barrier for adoption in Greece and suggest financial incentives and awareness activities facilitate the adoption of the technology. Michelsen and Madlener (2016) identify environmental protection, lower dependency on fossil fuels and knowledge as key drivers and old habits and uncertainty about the new heating system as principal barriers to switch from fossil fuel to a renewable residential heating system in Germany. Kelly et al. (2016) investigate the potential market for air source heat pumps in Ireland from a cost and policy perspective. Meles, Ryan and Mukherjee (2019) use a discrete choice experiment to examine the factors the influence consumer preferences for heat pump system among Irish households. The study finds that upfront cost, bill savings, environmental sustainability and installation hassle significantly affect consumers' preferences for heat pump systems.

In the literature, however, there is little analysis of the barriers, costs and societal benefits relating to heat pump systems nationally in Ireland and internationally. Nor has the technology been examined from a consumer perspective in terms of the level and timing of likely adoption at scale in Ireland. Consumer adoption is vital to the diffusion of the technology and a better understanding of the rate of uptake remains a gap for heat pump systems and other renewable heat technologies in Ireland. The present research addresses this gap and develops an agent-based model using nationally representative empirical data and historical data to understand the rate of adoption of heat pump systems in Ireland. Thus, it enables us to carry out a more comprehensive economic assessment of the technology and the economically and socially efficient policy options in the Irish context.

3. Materials and Model Description

The agent-based model is designed and simulated in NetLogo, a multi-agent programming platform.[3] Heterogeneous agents are created from nationally representative Irish households. We use the empirical data to produce parameters for a statistically representative Irish population. The empirical data is collected through an online survey from 1,208 Irish households in July 2018. The sample households are representative of Irish households with respect to age, regions and social classes. Due to missing values for some key variables, the final simulation is conducted with 933 households.

The survey data consists of information on households' socio-demographic characteristics, building characteristics, geographical location, a primary source of home heating, bimonthly heating bill, pro-environmental behavior, risk-taking behavior, as well as the number of peers with whom households communicate about new energy technologies. It also contains psychological factors including attitude to heat pumps, perceived behavioral control and subjective norms and intention to install heat pump systems at home, and whether the household has currently a heat pump system installed at home. Thus, in the agent-based model, each agent is characterized by several attributes that are assigned from the survey data. See Table 1 for households' specific attributes. In addition, we use secondary sources of data on historical

[3] NetLogo is widely used and freely available programming platform with various open sources and video examples (Wilensky, 1999).

adoption of heat pump systems, initial capital costs and related information. The main aim of the empirical data is to test the model and to provide input parameters for the simulation.

< Table 1 here >

3.1 Agent-based model

In our model, we consider agents (households) as ‘adopters’ if they have already installed a heat pump system at home and as ‘potential adopters’ if their existing main heating system is solid fuels, oil, gas, or electricity. We assume that no switching back to non-adopter once an agent becomes an adopter. A potential adopter decides to install a heat pump system when the utility from adoption exceeds a certain threshold level. The threshold is determined based on the individual agent’s propensity to adopt the technology. Some agents adopt before or after a small portion of others while others wait to adopt until a large portion of the population adopted. A lower threshold value represents early adopters while a higher threshold value indicates laggards.

We use responses from the survey to identify individual agents’ propensity to try new technology. In the survey, we asked respondents what best describes their willingness to try new technology. They could choose one of the following options: ‘usually one of the first people’, ‘generally waits until some people purchase and use it’, ‘hold off until majority of the people’, one of the last people’, and ‘prefer to use what I have in the past instead of new technology’. We categorize the responses into four; those who chose one of the last two options are grouped into one category. Based on these, we assume that agents have a different threshold (θ_i) that is normally distributed with mean μ_g for group g and standard deviation of 0.25, that is, $\theta_i \sim N\ (\mu_g, 0.25)$.[4] The average thresholds vary across the different groups of the survey responses on willingness to try new technology. While those who chose the option ‘usually one of the first people’ have the lowest threshold, those who chose the last two options have the highest. The thresholds are determined based on several trials and errors in the model calibration.

To evaluate an agent’s adoption decision of a heat pump system, we consider three main factors: economic (financial), psychological (behavioral) and social networks. The utility of agent i, $U(i)$, is the sum of the weighted utilities from each of the three factors and is provided as follows.

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[4] $\mu_1 = 0.95, \mu_2 = 1.05, \mu_3 = 1.15, and\ \mu_4 = 1.25$ for the respective categories. McCoy and Lyons (2014) have also used a normally distributed threshold, $\theta_i \sim N\ (0.65, 0.15)$, for adoption of electric vehicles among Irish households.

$$U(i) = w_{econ} * U_{econ}(i) + w_{behavior} * U_{behavior}(i) + w_{network} * U_{network}(i) \quad (1)$$

where, $\sum_k W_k = 1$ for $k \in \{econ, behavior, network\}$ and $W_k, U(i) \in [0, 1]$.

The utility from each of the three factors is normalized to lie within the [0, 1] interval. As a result, the total utility of a potential adopter is defined within the [0, 1] interval. The weights W_k assigned to the partial utilities from each of the three factors are determined in the model's calibration. Next, we explain how the utility from each of the three factors is computed.

3.1.1 Economic utility

In the economic factor, an agent compares the annual heating billing of an existing heating system with the annualized capital cost (includes available grants) and the running cost of the heat pump system. We assume the capital cost of the existing heating system as a sunk cost and compute the annualized installation (capital) cost of the heat pump system (AC_{HP}) as follow:

$$AC_{HP} = \frac{(C - Grant) * r * (1 + r)^L}{(1 + r)^L - 1}. \quad (2)$$

Where C is the capital cost of a heat pump system (including installation costs) that depends on the size and type of heat pump system. It ranges from €15,000 to €23,000 for ground source heat pumps (GSHPs) and varies from €9,000 to €13,000 for air source heat pump (ASHPs). $Grant$ is grant amount for heat pump systems. L indicates the life expectancy of the heat pump system which is approximately 25 years for GSHPs and about 20 years for ASHPs.[5] r is the discount rate of capital investment for the heat pump system. In our model, we choose 4%, which is the discount rate for public sector projects in Ireland (Department of Public Expenditure, 2018).

A heat pump system uses electricity to operate and has a Coefficient of Performance (COP) of 2 to 4 (Bakirci, 2010; Self et al., 2013). The annual operating costs of a heat pump system are significantly lower than conventional fossil fuel and electric-based heating systems and could result in cost savings of up to 70 percent (Bakirci, 2010). While the average cost savings of ASHPs is about 30%, it is around 50% for GSHPs.[6] Here, we use the annual heating bill as a measure of operating costs. The typical bi-monthly heating bill of an existing heating system is obtained from the survey and converted into an annual heating bill by multiplying the bi-monthly

[5,6] See, https://greener.ie/heating/ground-source-heat-pump/
https://greener.ie/heating/air-source-heat-pump/

bill by six. The annual costs of heat pump system and existing heating systems are provided as follows.

$$\mathrm{A}_{\text{Cost HP}} = \mathrm{AC}_{\text{HP}} + (1 - \text{bill saving}) * \text{annual heating bill} * (1 + \%\Delta \text{ in electricity price}) \quad (3a)$$

$$A_{\text{Cost existing system}} = \text{annual heating bill} * (1 + \%\Delta \text{ in fuel price}) \quad (3b)$$

Since the price of electricity and price of other fuels could change over time, we include the percentage change in the price of fuels (%Δ in fuel price) and percentage change in electricity price (%Δ in electricity price) in computing the annual cost of the heat pump system and existing home heating systems. Furthermore, we incorporate the available Irish government home grant of €3,500 for heat pump systems (SEAI, 2018). Thus, the economic utility is calculated as:

$$Economic\ Utility = \frac{A_{\text{Cost existing system}}}{\mathrm{A}_{\text{Cost HP}}} \quad (4)$$

The value of the economic utility is normalized between zero and one. The higher the value, the more likely is the agent to install a heat pump system. That is, the higher the cost of the existing heating system, the more likely is for a household to replace it and install a heat pump.

3.1.2 Psychological utility

The psychological factor is based on the theory of planned behavior (Ajzen, 1991), which states human behavior is the result of an intention to perform the behavior. In turn, the intention per se is driven by an individual's attitude towards the behavior, subjective norms and perceived behavior control.[7] The theory of planned behavior is widely applied for identifying psychological factors that underlined decisions regarding technology adoption (Sopha and Klöckner, 2011). In the survey, respondents were asked statements about their intention to install a heat pump system, attitude towards it (heat pump save money and is good for the environment), perceived behavioral control (home is compatible) and subjective norms (relatives or friends appreciate installing heat pump), on a scale of 1-5, where 1 'strongly disagree' and 5 is 'strongly agree'.

[7] Behavioral intentions determine actual behavior and can serve as a proximal measure of behavior. Attitudes towards behaviors represent an assessment of the outcomes of a behavior and an estimate of the probability of the results of a behavior. For example, people who believe heat pump system is good for the environment or could save money, have positive attitude towards it and are likely to install heat pump system. Subjective norm represents the 'normative beliefs' considering the influence of significant others including family members, friends, neighbors, institutions (e.g., religion, political party). Perceived behavioral control refers to an individual's belief as to how difficult or easy carrying out a behavior will be. This includes the influence of resources availability, skill or other external constraints (see, Michelsen and Madlener, 2010).

Using latent class analysis, we identify four classes of people from the survey responses to the statements. See Meles, Ryan and Mukherjee (2019) for details. For the partial utility from the behavior factor, we consider the conditional probabilities of belonging to the pro-heat pump class. This class shows the highest probabilities of responding ‘agree’ and the lowest probabilities of answering ‘neither’ and ‘disagree’ for all statements. The probability of belonging to this class is close to zero for those who are against heat pump, close to one for those who are pro-heat pump; and in between for those who are ‘neutral’ and ‘moderate’.

Following Collins and Lanza (2010), the latent class analysis is formulated as follows. Suppose that there are C latent classes ($c = 1, \dots, C$) that are inferred from $j = 1, \dots, J$ observed variables, and the variable j has $r_j = 1, \dots, R_j$ response categories. Assume $y = (r_1, \dots, r_j)$ represents the vector of a particular individual's responses to the J observed variables. The probability of observing a particular response pattern is:

$$\Pr\{Y = y\} = \sum_{c=1}^{C} \gamma_c \prod_{j=1}^{J} \prod_{r_j=1}^{R_j} \theta_{j,r_j|c}^{I(y_j=r_j)} \tag{5}$$

Where γ_c is the probability of membership in latent class c and $\theta_{j,r_j|c}^{I(y_j=r_j)}$ is the probability of response r_j to item j given membership in latent class c.

3.1.3 Social Network Utility

The social network factor captures the influence of the behavior of other agents within social interactions. Social networks significantly influence adoption decisions (Valente, 1996). Each agent has a number of other agents that are considered part of its social network. The social network is assumed based on the proxy in location. The size of the personal network is measured by the number of peers with whom a household communicate about new energy technology that is obtained from the survey. Instead of using the reported number of peers for each household, we compute the average size of peers in each of the eight geographical locations, the rural and urban areas of the four regions of Ireland. Thus, peer size varies across locations but the same for households in the same location. It ranges from 4 to 17. The utility from social networks is computed as:

$$Social\ Network\ Utility = \frac{N_{ia}(t)}{N_i}. \tag{6}$$

Where N_i is the total number of peers (neighbors) of agent i and $N_{ia}(t)$ stands for the number of neighbors of agent i who adopted heat pump system at time t. The larger the number of peers that adopted heat pump system, the higher is the influence of social network and the more likely is an agent to install a heat pump system at home.

3.2 Simulation Model

The agent-based model is implemented in NetLogo 6.0.2. Figure 1 depicts the simulation model in NetLogo. The simulation is initialized by importing the household survey data from an external file into NetLogo. Heterogeneous agents are created based on the empirical data from the household survey and assigned to their corresponding location. The agents are positioned in 32*32 virtual grids. The simulation environment is divided into eight distinct geographic sections that represent the rural and urban areas of the four regions of Ireland (Dublin, Leinster, Munster and Conn ulster). The location of the agents on the map is based on whether they live in rural or urban areas of the four regions of Ireland. However, the position within a given segment is random. The upper segments in Figure 1 are for agents who live in rural-Dublin, rural-Leinster, rural-Munster and rural-Conn ulster respectively and the lower sections represent the corresponding urban areas. The model comprises 933 agents that are heterogeneous with respect to the attributes described in Table 1. For simplicity, we assume those attributes of agents remain fixed during the simulation.

< *Figure 1 here* >

The simulation starts to represent the condition at the time of the survey in 2018. The survey shows that 33 agents, out of the 933, have adopted a heat pump system at their home. Of the 33 heat pumps, the 14 are GSHPs while the 19 are ASHPs. We consider the 33 agents as initial adopters and the rest as 'potential adopters'. At every time step t, a potential adopter re-evaluates its status and decides whether to adopt or not.[8] When deciding to install a heat pump system, agents consider the utility from adoption and their household annual income. If the total utility from the economic aspects, behavioral factors and social network surpasses the threshold, the agent will install heat pump system at home. We also consider upfront costs of more than 34% of

[8] The time step is the length of the time duration it takes to update all agents and thus may not correspond with real time. In the calibration of the model with historical data, we assume 12 time steps correspond to one year.

the annual household income as unaffordable.[9] Therefore, an agent becomes adopter if the utility from adopting exceeds the adoption threshold, $U_i(t) > \theta_i(t)$, and the upfront cost of the heat pump is less than or equal to 34% of the annual household income.

To obtain a representative simulation, we perform 100 replications for a single simulation result. This is due to the presence of a random process in the model simulation using identical parameters and initial conditions. For example, the position of agents within a given section of a geographical location, the thresholds, and the influence of social interaction, which depends on the proxy in location, are random. The single simulation runs for 156-time steps. Results are therefore presented for the average of the 100 replications.

4. Results

We start our simulation with the calibration of the weights for the partial utilities from the economic aspects, psychological factors and social networks. We use historical data on GSHPs to calibrate the parameters in the model. Data on uptake of GSHPs in the residential sector in Ireland is limited; we have access only for the period 2002-2012. Thus, we utilize historical data on GSHPs from Finland and Sweden that are available for a longer period, 1981-2018. We first try to understand where the historical GSHPs uptake in Ireland is on the GSHPs adoption curve in Finland and Sweden. Figure 2 and Table 2 show that the cumulative uptakes of GSHPs in Ireland in the years 2004-2012 fit better with the cumulative uptakes of GSHPS in Finland and Sweden in the years 1981-1989, after adjusting the GSHPs adopters by the number of households in the respective country.[10] This highlights that, compared to Finland and Sweden, the adoption of heat pumps in Ireland is at its early stages.

Next, we determine where the year 2018, when the Irish survey data for the simulation was collected, fits on the adoption curve of GSHPs in Finland and Sweden. After a number of trials using the calibrated weights for the partial utilities, it better fits with the year 2001 on the adoption curve of GSHPS in Sweden. To determine the weights assigned to each of the three partial utilities, we run several simulations through trial and error by varying each weight. Finally, we find the weights 0.38 for economic factor, 0.27 for behavioral factor and 0.35 for

[9] The upfront cost of €15,000, which is used in the baseline scenario, is about 34% of the average midpoints of the annual household income (€43,735) of the sample household in the survey.

10 The number of households in Finland, Sweden and Ireland in 2018 were about 2.68 million, 4.66milllion and 1.76 million respectively (see, https://ec.europa.eu/eurostat). Thus, the cumulative GSHP adopters in Sweden and Ireland are multiplied by 0.575 and 1.522 to adjust for household numbers in reference to Finland.

social networks that generate similar distribution to that of historical data on adoption of GSHPs in Sweden and Finland (see Figure 2). We run a single simulation over 156-time steps and assume that 12-time steps equal to one year. That means, the simulation results from 0 - 11 time steps correspond to the cumulative number of adopters in Ireland in the year 2018. Overall, the 156-time steps in the simulation correspond to the uptake of heat pumps over the years 2018-2030 in Ireland and over the years 2001-2013 on the adoption curve in Sweden. Since our simulation is based on empirical data in 2018, the estimated cumulative number of adopters may not precisely represent the actual distribution.

< Figure 2 here >

< Table 3 here >

We run 100 simulations, each over 156-time steps, for the baseline scenario. We process the agent-based model outputs of the 100 simulations in SATA 15. The parameters for the baseline scenario are given in Table 3. As we have both GSHPs and ASHPs in our data, we use the midpoint values of upfront cost (€15,000), bill savings (40%) and lifespan (22.5 years) of GSHPs and ASHPS in the baseline scenario.[11] Figure 3A shows the average cumulative number of heat pump adopters over the 156-time steps for the 100 simulations. At the end of the simulation, the average heat pump adopters are 138 agents (14.8% of the 933 agents in the model) with a standard deviation of 7.92. The corresponding numbers of Irish households that will install heat pumps at their home over the years 2018-2030 are provided in Figure 3B.[12] It shows that approximately 260,000 households in Ireland will install either ASHPs or GSHPs at their home in the year 2030, which corresponds to the cumulative number of adopters at the 155-time steps in the simulation. This is approximately 14.8% of the 1.76 million households in Ireland.

< Figure 3 here >

We further run a probit model to explore how the uptake of a heat pump is associated with socio-demographic characteristics, building characteristics, location and survey measures of risk and time preferences. Table 4 presents the estimated results of probit model of the data from the simulation of the model over 156 time steps, the baseline scenario. The dependent variable is a dummy that equals to one if the agent (household) in the simulation adopts a heat pump, zero

[11] In this paper, we model heat pumps in general. In practice, heat pumps could vary in upfront costs, efficiency and lifespan depending on types and sizes of heat pumps.

[12] Assuming the 933 households in the model are representative households, we extrapolate the simulation results to the 1.76 million Irish households by multiplying it by a factor of 1,886.

otherwise. The results show that homeowners, households in Dublin country and households with a higher level of education and a larger number of bedrooms are more likely to uptake heat pump. We also observe that semi-detached and detached houses compared to an apartment, recently built homes relative to old buildings, rural areas compared to urban areas and households who are willing to take a risk and more patient are more likely to adopt heat pump but the estimated coefficients are not statistically significant.

< *Table 4 here* >

We also develop scenarios to test the sensitivity of the baseline model with respect to change in upfront costs, bill savings and the Irish government home grant of €3,500.[13] Figure 4A shows how different grant amounts affect the adoption process. The simulation results show that the available Irish government home grants of €3,500 increase the average number of adopters in 2030 to about 14.8% of the Irish households compared to the 12.2% (about 215,000 heat pumps) without a grant. Also, the grant amounts of €5,000 and €7,500 increase the number of heat pump adopters in 2030 to approximately 16.5% and 20.2% of the Irish households respectively compared to the 14.8% in the baseline (a grant of €3,500). Figure 4B presents the effect of change in upfront costs and bill savings of heat pumps on the uptake. Different values are considered to account for different types and sizes of heat pumps. For example, the upfront costs of €9,000 and €13,000 with 30% bill savings correspond to different sizes of ASHPs. Similarly, the upfront costs of €19,000 and 23,000 with 50% bill savings are analogous with GSHPs. The simulation results show that, depending on the type and size of the heat pump considered, about 6% to 31% of the 1.76 million Irish households will install a heat pump at home in 2030. The result supports the argument that a high upfront cost of heat pump system is the main barrier for the adoption of a heat pump system. In general, the impacts of upfront costs and grants on uptake of heat pumps depend on the magnitude of the weight of the economic factor in the model.

< Figure *4 here* >

5. Conclusion

Many countries are looking for alternatives sources to carbon-intensive heating systems to curb greenhouse gas emissions. The deployment and development of renewable energy technologies such as heat pump systems are among the viable options for space heating and

[13] We also check sensitivity of the results with different discount rates (2%, 6% and 10%) and change the electricity prices by 5%, 10% and 25% (not reported here due to space but available at authors' request).

domestic hot water production in the residential sector. In this paper, we model the uptake of heat pump systems in the residential sector. Heat pump systems offer several advantages compared to conventional heating systems; however, their current levels of adoption are low. While the high upfront cost of heat pump system has been commonly considered as the main barrier (Karytsas and Choropanitis, 2017), the adoption and diffusion of new energy technologies goes beyond financial factors and includes behavioral elements and the influence of social interactions (Kiesling et al., 2012). It is therefore important to include more than costs of the technology in decision-making models of uptake.

In this paper, we develop an agent-based model to investigate the adoption and diffusion of heat pump systems among Irish households. In our model, we consider three main factors: economic, psychological and social influences to describe and explain the adoption and diffusion of heat pump systems. Uniquely, we use nationally representative household survey data from Ireland to specify and test the model. Unlike, the traditional aggregated model, an agent-based model enables us to account for individual heterogeneity and designs for “what if”-type questions. Thus, the results of the simulation allow us to discuss how individual household socio-demographic characteristics, building characteristics, geographical location of household and policy incentives affect the adoption process.

Our model predicts that, on average, about 14.8% of the 1.76 million Irish households (approximately 260,000) will install a heat pump at their home in 2030. When we test the sensitivity of the results with respect to change in upfront costs, grants and bill savings, the number of uptakes in 2030 varies from 6% to 31% of the Irish households. For instance, the available Irish government home grants of € 3,500 increase the number of heat pump adopters in 2030 to 14.8% compared to the 12.2% without any grant. The result also shows that younger households, homeowners, households in Dublin County and households with higher education and a larger number of bedrooms are more likely to adopt a heat pump.

The study contributes to the literature on the adoption and diffusion of renewable energy technologies by taking into account the influences of individual consumer characteristics and policy incentives and by using nationally representative empirical data. More specifically, it helps to better understand the underlying factors that explain the uptake of heat pump systems in countries with low uptake to date like Ireland. It also provides important information to policymakers on the factors that influence adoption and how policy incentives such as the availability of grants affect the adoption process. The findings highlight that policy interventions that increase the levels of awareness about the availability of the technology and its features, the associated benefits, the availability of home grants and insurance to curtail the uncertainty regarding the technology could be important to facilitate the adoption process.

There are some limitations to our study. The empirical data used for the model simulation represented the situation at the time of the survey completion in 2018. The situation before the survey data and in the future could be different. In addition, we look at the adoption process in existing homes; we do not consider new buildings. Thus, the overall level of adoption could be higher, for example, if a new regulation is introduced whereby new buildings are required to install a heat pump system.

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Appendix

Table 1. Households' specific attributes

Attributes	Variables definition and corresponding values
Socio-demographic characteristics	Gender: male, female Age categories: 18-24, 25-34, 35-44, 45-54,55+ years Education: primary, secondary, third level degree, master's degree, doctorate Annual household income 14 categories: zero, €1,000 - €9,999, €10,000- €19,999…, €90,000-€99,999, €100,000-€124,999, €125,000- €149,999 and €150,000+. Midpoints of the annual household income: ranges from zero to €150,000 with an average of €43,735
Building characteristics	Year built categories: before 1976, 1976-1979, 1980-1991,1992-2001, 2002-2005, 2006-2008, 2009-2014, 2015-2018 Home type: apartment, terraced house, semi-detached, and detached Homeownership: Own outright, own with a mortgage, and rented Number of bedrooms: ranges from one to 12 with a mean value of 3
Geographical location	Area lives in: rural, urban Regions: Dublin, Leinster, Munster, and Conn ulster Area lives in a region (eight categories): Rural Dublin, Rural-Leinster, rural-Munster, Rural-Conn ulster, Urban Dublin, Urban-Leinster, Urban-Munster, and Urban-Conn ulster
Others	Primary home heating system: solid fuels, oil, gas, electricity and heat pump Average annual heating bill: ranges € 90 - €9,000 with a mean value of €758 Install ground source heat pump system at home: No, Yes (14 households installed) Install air source heat pump system at home: No, Yes (19 households installed) Propensity to try new energy-related technology: early adopter, wait for some to adopt, wait until majority adopt, laggards Willing to take a risk on a scale 1(completing unwilling) to 5 (completing willing) Willing to give up today on a scale 1(completing unwilling) to 5 (completing willing) Number of peers (averaged over areas live in a region): ranges from four to 17 with a mean value of 6. Behavioral factors: the probability of belonging to the pro-heat pump class

Table 2. Historical cumulative GSHPs uptake data in Ireland, Finland and Sweden

Year	Finland GSHP	Sweden GSHP	Sweden GSHP adjusted for HHs number	Ireland GSHP	Ireland GSHP adjusted for HHs number
Until 1981	5,808	13,541	7,786.075		
1982	7,911	16,071	9,240.825		
1983	10,111	20,671	11,885.83		
1984	11,814	28,474	16,372.55		
1985	12,320	34,292	19,717.9		
1986	12,520	36,408	20,934.6		

1987	12,720	37,932	21,810.9		
1988	12,920	38,906	22,370.95		
1989	13,120	40,002	23,001.15		
1990	13,320	42,281	24,311.57		
1991	13,520	44,441	25,553.57		
1992	13,720	45,833	26,353.97		
1993	13,871	47,943	27,567.22		
1994	13,974	50,709	29,157.68		
1995	14,077	53,485	30,753.88		
1996	14,331	59,948	34,470.1		
1997	14,731	70,949	40,795.68		
1998	15,434	82,911	47,673.82		
1999	16,339	94,356	54,254.7		
2000	17,539	108,856	62,592.2		
2001	19,016	135,055	77,656.63		
2002	20,495	162,551	93,466.83	546	831.01
2003	22,695	194,115	111,616.1	1,536	2,337.79
2004	25,600	233,474	134,247.5	2,836	4,316.39
2005	29,106	268,037	154,121.3	4,736	7,208.19
2006	33,612	308,054	177,131	6,914	10,523.11
2007	38,906	335,992	193,195.4	9,614	14,632.51
2008	46,412	361,116	20,7,641.7	12,365	18,819.53
2009	52,549	388,638	22,3,466.8	13,287	20,222.81
2010	60,640	420,592	241,840.4	14,580	22,190.76
2011	74,581	451,993	259,896	15,569	23,696.02
2012	87,534	476,513	273,995	16,485	25,090.17
2013	99,875	501,410	288,310.8		
2014	111,000	524,766	301,740.4		
2015	120,210	551,143	316,907.2		
2016	128,701	573,986	330,041.9		
2017	136,687	596,627	343,060.5		
2018	144,682	620,789	356,953.7		

Table 2 presents the cumulative uptake of ground source heat pumps (GSHPs) over years in Finland, Sweden and Ireland. The number of GSHPs adopted in Sweden and Ireland are adjusted by the number of households in reference to Finland using 2018 data.

Sources: https://www.sulpu.fi

https://skvp.se/aktuellt-o-opinion/statistik/varmepumpsforsaljning

Pasquali et al. (2015)

Table 3. Parameter values for the baseline and different scenarios

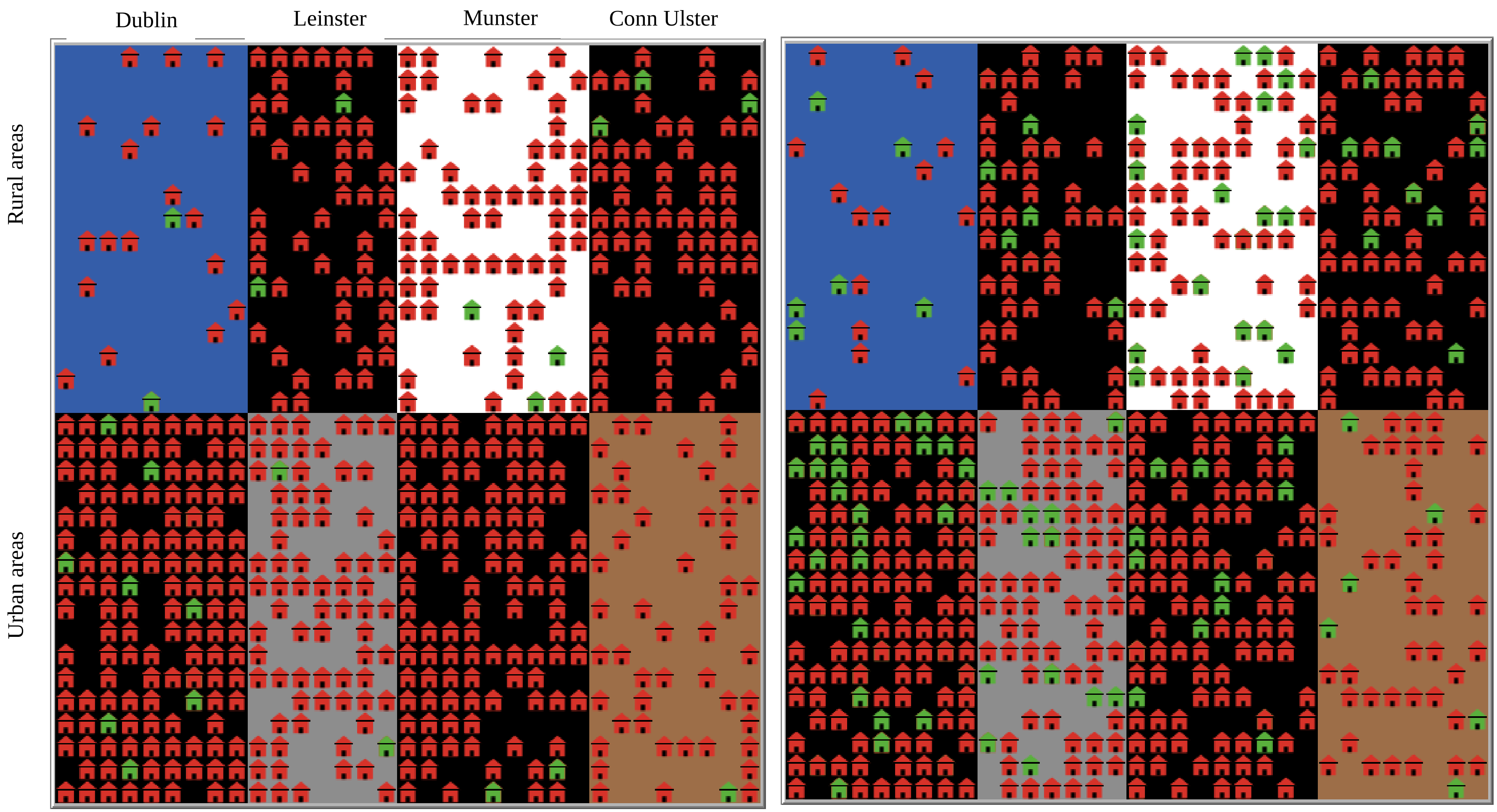
Variables	Baseline	Sensitivity analysis
Upfront cost of heat pumps	€15,000	€9000, €13000, €19000, €23000
Grant amount	€3,500	€0, €1500, €5500, €7500
Discount rate	4%	2%, 6%, 10%
%Δ in electricity price	0	-25%, -10%, -5%, 5%, 10%, 25%
%Δ in fuel price price	0	
Bill savings	40%	30%, 50%
Average weights for partial utilities:		
Economic utility	0.38	
Psychological(behavioral) utility	0.27	
Social network utility	0.35	

Table 4. Probit model estimations of the simulation

Variables	Probit model
Respondents characteristics:	
1 if male	0.252**
	(0.107)
1 if age is between 34 and 54 years (reference: age of 34 years or less)	-0.215
	(0.131)
1 if age is 55 years or above	-0.199
	(0.144)
1 if Third level degree (reference: primary or secondary school)	0.187
	(0.118)
1 if master's degree or doctorate	0.358**
	(0.145)
Building characteristics:	
1 if terraced house (reference: apartment)	-0.015
	(0.209)
1 if semi-detached house	0.040
	(0.197)
1 if detached house	0.268
	(0.218)
1 if own outright (reference: rented home)	0.077
	(0.152)
1 if own with a mortgage	0.426***

	(0.145)
1 if built between 1976 and 2001 (reference: built before 1976)	0.169
	(0.135)
1 if built between 2002-2018	0.054
	(0.150)
Number of bedrooms	0.154***
	(0.058)
Location:	
1 if lives in rural areas	0.079
	(0.132)
1 if Dublin county	0.385***
	(0.122)
Willing to take a risk (5-point Likert scale)	0.051
	(0.074)
Willing to give up today (5-point Likert scale)	0.121
	(0.083)
Constant	-2.579***
	(0.335)
Log-likelihood	-380.838
Observations	933

Table 4 presents the results of the probit model estimates of the simulation. The dependent variable is a dummy equal to one if the agent in the ABM adopts a heat pump over the 156 time steps, zero otherwise. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$



A. Initial distribution of agents in NetLogo

B. Final distribution of agents in NetLogo

Figure 1. Distribution of the 933 agents across eight different geographical locations in NetLogo. It represents the rural and urban areas of the four counties in Ireland. Panel A shows the initial distribution of agents across the eight geographical locations in NetLogo. Homes with red color stand for potential adopters whereas homes with green color are those who have already installed a heat pump (the 33 initial adopters from the survey). Panel B depicts the final distribution of agents after running the simulation for 156 time steps.

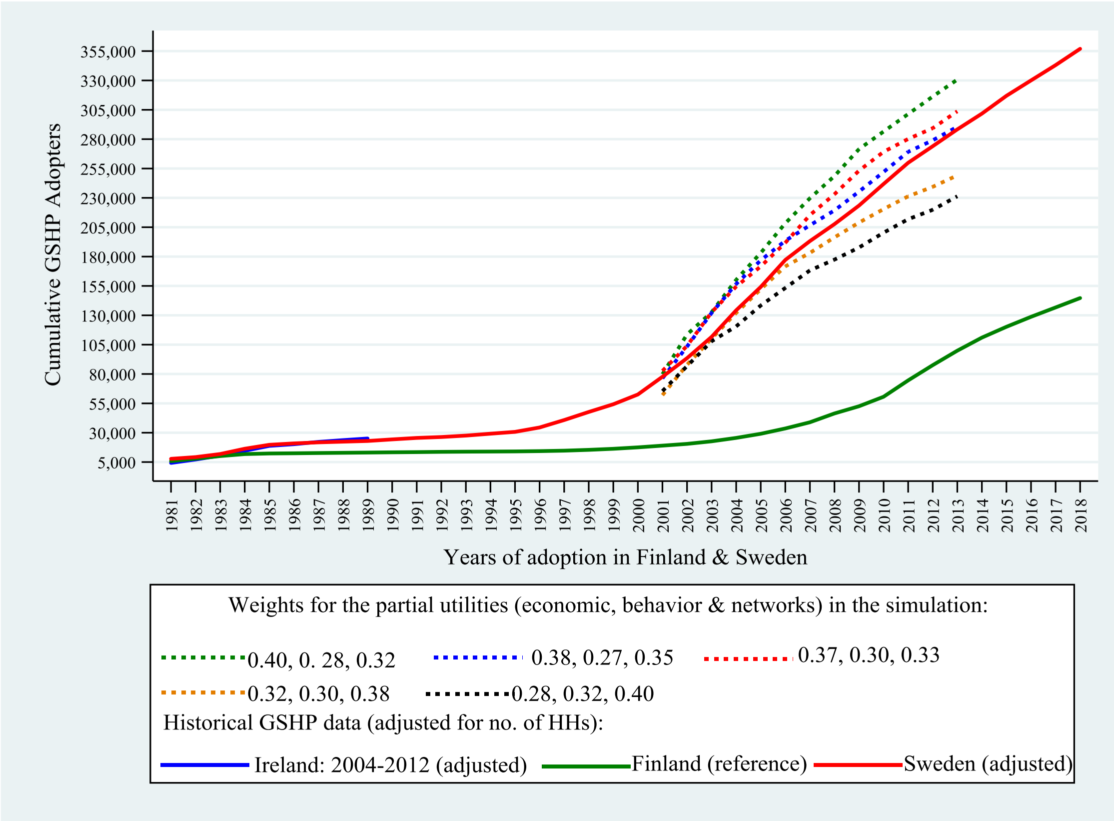
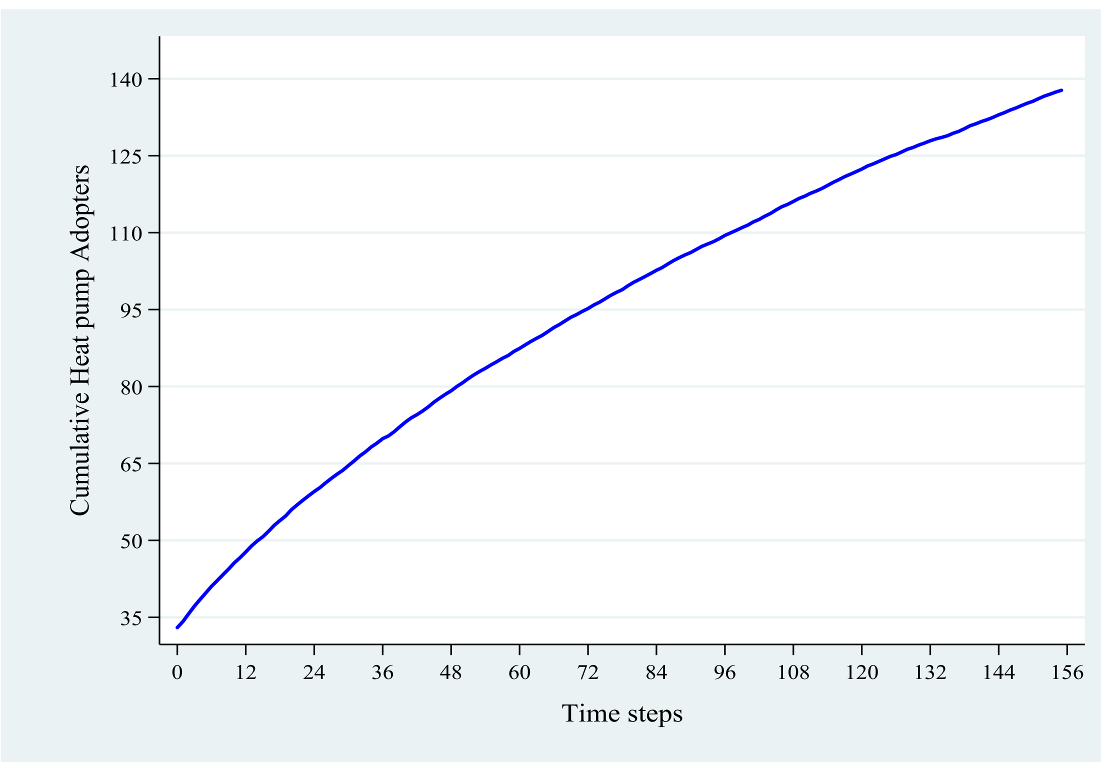
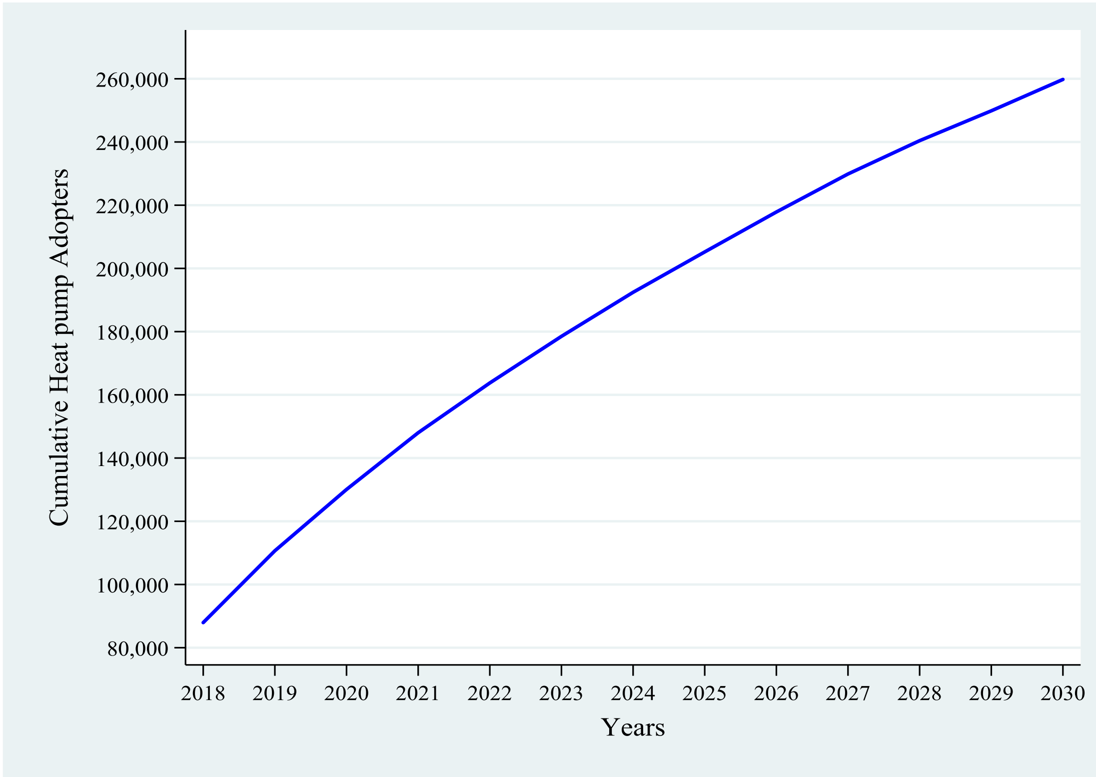


Figure 2. Calibration of the weights for the partial utilities based on historical data

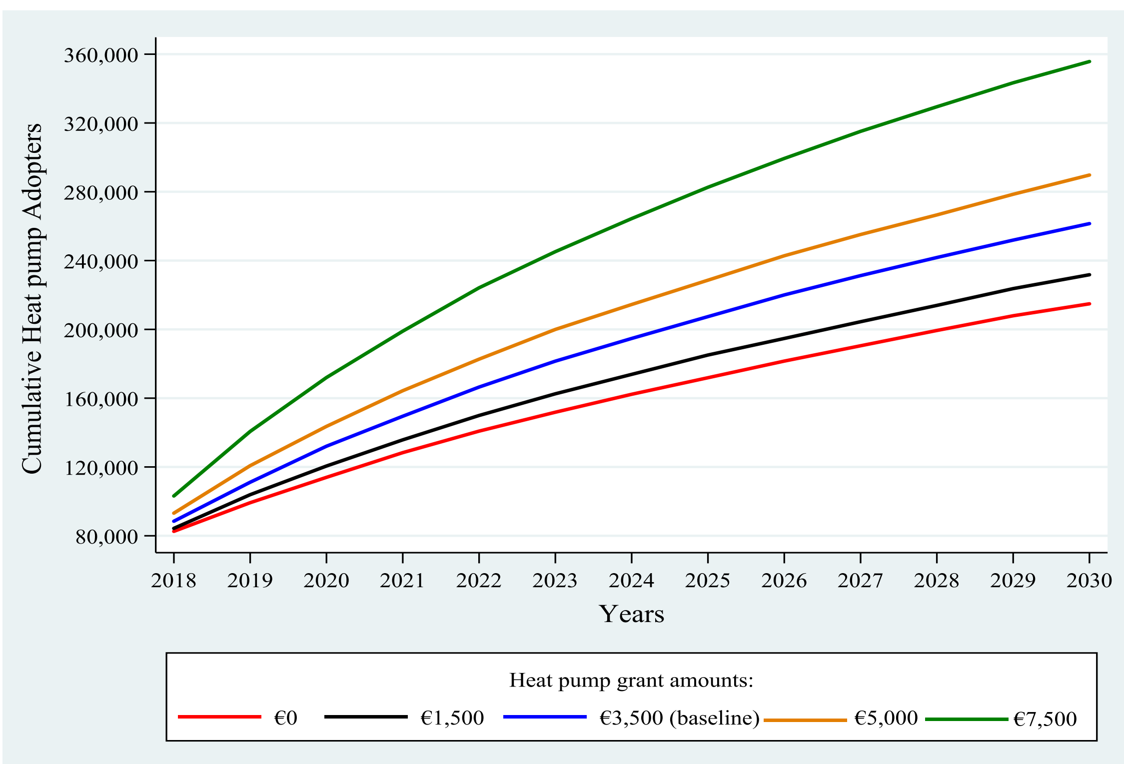


A. Model

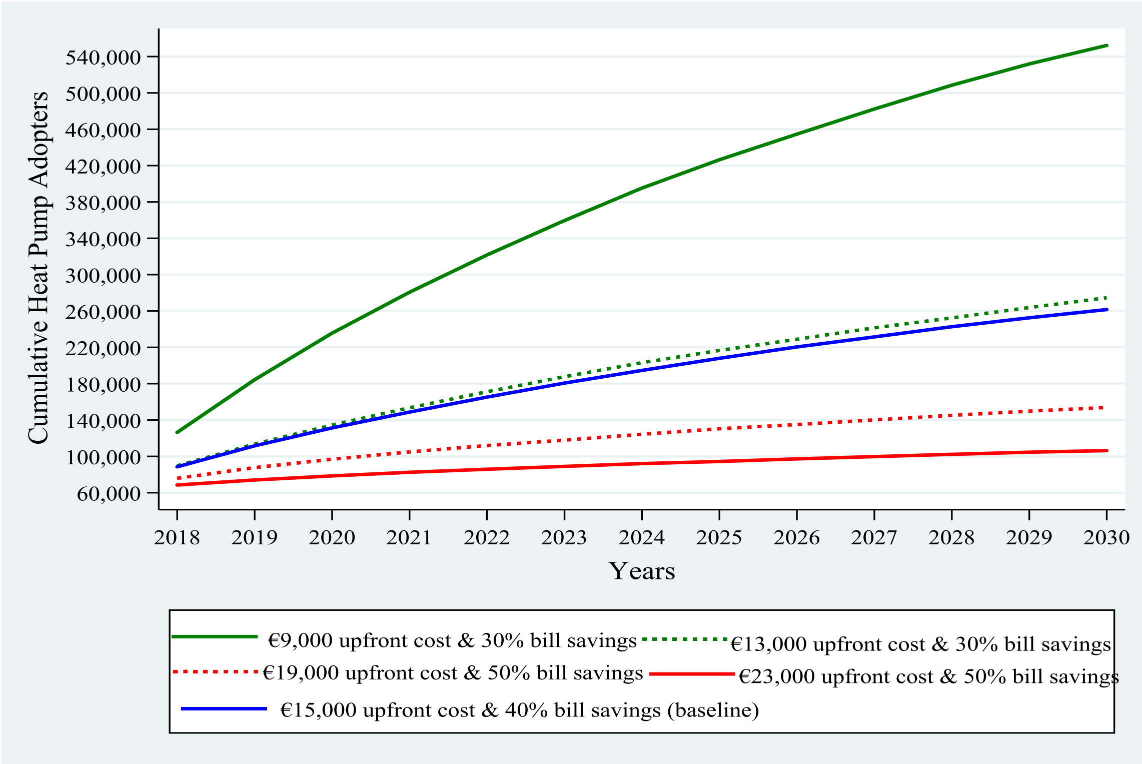


B. Population (Irish households)

Figure 3. Cumulative heat pump adopters (a) Simulation model (b) Irish households



A. Different grant amounts



B. Different upfront costs and bill savings

Figure 4. Cumulative number of adopters for different scenarios (a) different grant levels (b) different upfront costs and bill savings

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