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Abstract: The UK Government introduced the tariff-based domestic Renewable Heat Incentive (RHI) in April 2014 to encourage installation of renewable heat technologies as a key component of its carbon reduction policy. Of these, heat pumps are considered to be the most promising for widespread adoption and as such are the subject of this paper. Pilot studies prior to introduction of the policy identified non-financial barriers to uptake, such as the "hassle factor" involved, and initial figures indeed indicate that uptake is lower than expected. We analyse these non-financial barriers using an agent-based model and conclude that there is a tipping point beyond which adoption is likely to fall very sharply. We suggest that the RHI's complex and stringent compliance requirements for home inspections and heat emitter performance may well have driven adoption past this point and that further intervention may be required if the key aims of the RHI are to be achieved.

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Highlights (for review)

* We examine the uptake of the UK Renewable Heat Incentive (RHI)
* We use Agent-based modelling to simulate uptake in a heterogeneous population
* Simulation modelling suggests that uptake is sensitive to non-financial barriers
* Non-fincancial barriers were introduced after RHI policy impact assessment
* New barriers combined with sensitivity could explain observed lower than expected uptake

Short Communication

Will domestic consumers take up the Renewable Heat Incentive? An analysis of the barriers to heat pump adoption using agent-based modelling

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Abstract

The UK Government introduced the tariff-based domestic Renewable Heat Incentive (RHI) in April 2014 to encourage installation of renewable heat technologies as a key component of its carbon reduction policy. Of these, heat pumps are considered to be the most promising for widespread adoption and as such are the subject of this paper. Pilot studies prior to introduction of the policy identified non-financial barriers to uptake, such as the "*hassle factor*" involved, and initial figures indeed indicate that uptake is lower than expected. We analyse these non-financial barriers using an agent-based model and conclude that there is a tipping point beyond which adoption is likely to fall very sharply. We suggest that the RHI's complex and stringent compliance requirements for home inspections and heat emitter performance may well have driven adoption past this point and that further intervention may be required if the key aims of the RHI are to be achieved.

Keywords: renewable heat incentive; feed-in tariff; agent-based model

1. Introduction

In April 2014 the UK's Department of Energy and Climate Change (DECC) announced the inauguration of the domestic Renewable Heat Incentive (DECC 2014a), with the claim that it is "the world's first long-term financial support programme for renewable heat,

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offering homeowners payments to offset the cost of installing low carbon systems in their properties". Similarly to feed-in tariffs that incentivise photovoltaic generators, the RHI scheme offers a tax-free, index linked, per kWh tariff payment with 2014 rates between £0.073 and £0.192 depending on technology. These payments are based on metered or estimated thermal energy outputs from heat pumps, biomass boilers, and solar thermal panels, with a tariff lifetime of seven years. In this paper we are concerned specifically with the ability of the RHI to encourage the adoption of heat pumps on a sufficient scale to achieve their expected major contribution to the government's ambitious strategy for reduction of carbon emissions from the 22% of total energy use that is required for domestic heating. Heat pumps are expected to be adopted initially in rural areas off the gas network, and then penetrate suburban housing to become the main alternative to a heat network connection (Figure 1).

<Figure 1 here>

Calculation of the tariff payable on a heat pump installation is based on some simple principles. A heat pump delivers a thermal energy output E_o that is a multiple of the input energy E_i, normally electricity. This multiple, known as the Coefficient of Performance (CoP), is typically in the range 2-4. It is the additional thermal output that can be considered renewable heat under this scheme because it is in effect extracted from the air in the case of an air source heat pump (ASHP) or from the earth by a ground source heat pump (GSHP). The renewable heat E_r potentially attracting a tariff is therefore given by:

$$E_r = E_o - E_i \qquad \textbf{\textit{(1)}}$$

The UK policy is also affected by the European Union (EU) Renewable Energy Directive (EU 2013), which requires that a heat pump must achieve a CoP of at least 2.5 for any of its output to be considered renewable. This is not a trivial requirement in the UK; a project to monitor 75 domestic heat pump installations revealed median CoP values of 2.2 for GSHPs and 2.0 for ASHPs (Energy Saving Trust 2010). This relatively poor performance compared to elsewhere in Europe has influenced the late introduction of more stringent eligibility requirements for the RHI as described in Section 3 below.

1.1. Predicted impact of RHI and initial outcome

Predictions for the uptake of the RHI over the 7 financial years to 2020/21 are given in DECC (2013b). Figure 2 shows the cumulative numbers of ASHPs and GSHPs expected to be installed under central estimates. High levels of uncertainty on the cumulative totals for 2021 are recognised by DECC, corresponding to the error bars shown.

<Figure 2 here>

Data are now available for the uptake during the first 5 months of the policy – to 31 November 2014 (DECC 2014b, Table 2.1). These show 1435 applications for the ASHP tariff and 292 for GSHP[1]. Since the predicted totals for 2014/15 were 15180 (ASHP) and 6600 (GSHP) these half-year figures are clearly dramatically below the levels anticipated even allowing for some temporary impediments in the application process immediately following introduction of the policy. This is surprising as, on the face of it, the RHI seems to be very attractive as an investment when viewed in purely rational commercial terms. It is framed initially to offer repayment of the consumer's additional investment over that which would be needed for a non-renewable heating system, with interest at 7.5% (DECC 2013b). This apparent attractiveness combined with the evidence of lower adoption rates than predicted suggests that there are other barriers discouraging uptake.

[1] These figures are the *applications* for RHI tariff – the figures for *acceptance* are somewhat smaller (1052 ASHP and 196 GSHP). This difference can be due to a number of factors, including the time taken by the application process or ineligibility of a small number of installations. Note that legacy accreditations granted are not included in this figure as we are concerned with RHI incentivised adoption here.

In this timely short communication we investigate the sensitivity of the RHI policy to these non-financial barriers using an agent-based modelling (ABM) approach, which provides a different perspective to that employed in DECC planning. We begin with a review of the modelling approach used by DECC's consultants, followed by an outline of the consumer decision process as simulated in our ABM. The results from the ABM simulations and their significance in relation to sensitivity to non-financial barriers are then presented. We discuss the nature of these barriers and conclude by suggesting possible mitigations and their policy implications.

2. Methods

2.1. Analysis of modelling non-financial barriers during policy formation

Three studies were the main source of barrier analysis during the formation of this policy, as cited in DECC (2013b). These were by Enviros Consulting (2008), Element Energy (2008), and Ipsos-Mori (2013). Element Energy focused mainly on consumers' willingness to pay a capital premium for lower running costs using a logit model. Logit models allow consumer decision probabilities to be estimated from expressed preferences when presented with choices (McFadden, 1974). This provided insight into the return on investment required, and also costed some non-financial factors such as the disruption from installing the ground loop for a GSHP (valued at £1600) and the benefit of recommendations from friends and tradesmen (up to £1700). Enviros Consulting considered non-financial barriers, but quantified only one at the consumer level – the additional "*hassle factor*" of selecting and installing renewable heat technologies. This was valued at 3 days' time at £14 per hour totalling £315. The other barriers concerned with consumer confidence and understanding were addressed by costed proposals for national marketing and demonstration projects. The Ipsos-Mori study provides valuable insights into consumer attitudes but does not attempt to quantify barriers. In particular, Ipsos-Mori found from consumer workshops that when asked to choose between home heating methods, it was the technology itself that mainly motivated 54% of consumer decisions, based on an intuitive assessment of the appropriateness of the technology for their home, whereas financial factors such as grants and running costs drove 37% of decisions. Crucially, the study also found that replacements were most often prompted by existing heating systems breaking down (30% of all changes) and when these were combined with non-emergency indicators that the system was reaching the point of breakdown ("Broken down / near the end of its life"), 61% of those changing their heating system cited this as the main reason (Ipsos-Mori, 2013 Fig. 21)

These pathfinder studies were not informed by knowledge of the eligibility requirements that would be included in the final policy. These include two criteria with a significant non-financial impact:

- An obligation to obtain an Energy Performance Certificate (EPC) and a Green Deal Assessment (GDA) for the property (Ofgem 2014). These two reports give the heat load and potential for energy efficiency improvements. If the GDA recommends that loft or cavity wall insulation be fitted, this must be completed to qualify for RHI payments.
- A minimum standard for heat emitter performance (DECC 2013d). Heat emitters are the devices (such as panel radiators) that heat individual rooms from the circulating hot water produced by the heat pump. A good heat emitter allows the circulating temperature to be relatively low which then ensures a CoP compliant with the EU directive mentioned in the introduction (EU, 2013) and a higher level of renewable heat production.

The first of these requirements increases the "*hassle factor*", as a minimum through the need to procure an inspection of the dwelling. If cavity wall or loft insulation have to be installed this will incur disruption and perception of additional cost, although in principle a GDA should only recommend self-financing improvements – i.e. the savings should be sufficient to repay a loan of the capital cost. The second requirement will only be satisfied for many homes by replacement of existing heat emitters, for example by replacing each radiator with a larger one or one with multiple panels. This will have an aesthetic and convenience impact in living spaces in addition to the cost, thereby influencing the "appropriateness" judgement of consumers which Ipsos-Mori found to be significant.

2.2. Agent-based modelling

Agent-based Modelling (ABM) is well suited for the fine grained modelling of heterogeneous households (Bonabeau, 2002; Gilbert, 2008, p. 14), which is necessary to assist understanding of the observed response to the RHI scheme and to explore the factors affecting the adoption rate. Detailed justification of this approach will be given in a further, extended paper. The simulation covers a small geographical area and runs with 48 time steps per day, for 3 years, with realistic weather input provided via a file containing a year's representative data. Heating demand is calculated from the desired set point temperature of the house (20 ^{o}C) and the outside temperature from the weather file - each agent maintains a physical model of its heating demand in order to capture the heterogeneous incentive to each individual household.

For the simulation runs, we initialised 4000 households, representing an off gas grid semi-rural area. About 2.2 million off gas grid dwellings in the UK are identified by DECC (2013e). Such areas should, by design, find the RHI scheme most attractive and so should exhibit a higher adoption rate for RHI-eligible technologies than on-grid properties. Houses were initialised with varying building physics characteristics (heat loss rate and thermal mass) and either oil fired or liquefied petroleum gas (LPG) fired heating systems (50% of houses oil, 50% LPG). These varying physical characteristics generate differing dynamic heat loads and corresponding projected economic benefits for each household.

The model is designed to take account of three factors influencing heat pump adoption:

1. The economic implications of adoption, based upon a simple payback period
2. The social observation of adoption (representing the impact of local recommendation identified by Element Energy (2008) and the "appropriateness" recognised by Ipsos-Mori (2013)).
3. The "*hassle factor*" of adoption recognised as significant in all studies.

These variables were assigned quantified values as follows:

2.3. Economic factor

$$x_{saving} = x_{direct} + x_{RHI} \quad \textbf{\textit{(2)}}$$

$$x_{payback} = \frac{7 * x_{saving}}{C} \quad \textbf{\textit{(3)}}$$

$$x_{econ} = 1 - \left(\frac{x_{payback}}{7} \right) \quad \textbf{\textit{(4)}}$$

where x_{direct} = estimated annual saving on heating bills from using a heat pump compared to the household's current technology and x_{RHI} = estimated annual RHI income for the heat pump, both based on heat load of the individual household. C is the cost of installation (the simulation generates an installation quotation randomly selected from a uniform distribution between £7000 – 11000 for ASHP and £11000-15000 for GSHP (EST, 2014)

2.4. Social factor

$$x_{social} = \frac{\sum\left(x_{neighbour}\right)}{count\left(neighbours\right)} \quad \textbf{\textit{(5)}}$$

$x_{neighbour}$ represents the opinion of an each neighbour on heat pump adoption. Where a neighbour has a heat pump, $x_{neighbour}$ is assigned randomly in the range [-1,1], resulting in 50% positive and 50% negative about installation and an average neutral influence. Where a neighbour has no heat pump, $x_{neighbour}$ is always zero (neutral). A neighbour of an agent is defined as any other household agent within 6 ± 3 km[2] of that agent geographically.

2.5. Hassle factor

x_{hassle} = *hassle factor* of installing various technologies – expressed as a value in the range [0,1] ***(6)***

In this simulation, values for *hassle* of each technology were fixed as GSHP = 0.9; ASHP = 0.7; heating oil = 0.2; liquefied petroleum gas (LPG) = 0.1.

2.6. RHI adoption decision

The variables were combined as a simple weighted sum for each agent, a technique common to similar ABMs (e.g. Lee et al., 2014; Stephan and Sullivan, 2004):

$$x_{decision} = w_{econ} \cdot x_{econ} + w_{social} \cdot x_{social} - w_{hassle} \cdot x_{hassle} \quad \textbf{\textit{(7)}}$$

where ***w*** variables represent the weight assigned by householders to the various factors. These parameters were held constant over the agent population in the current study, but varied between runs of the simulation as described below.

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[2] This value may seem unusual. Each agent has its own neighbourhood radius selected from a normal distribution R~N(5,2.5) where the mean and SD are in geographical units for the map projection used in the geography for the simulation – where the unit of measurement is 0.017453292519943295 degrees at a latitude of ~52 degrees North

The decision to adopt was taken as shown in Figure 3. A fault in their existing system is the dominant trigger for consumers to consider replacement. Surveys by Which? (2014) indicate that about 50% of gas and oil boilers need a repair in the first 6 years of their life. To allow for other events, such as a house move or high annual servicing cost, agents consider replacement on average every 5 years. The assignment of fault / failure is stochastic, so some agents will have their decision process triggered more often, whilst others will experience less frequent failure.

<Figure 3 here>

For this set of experiments, the decision threshold for all agents was set to 0.5. This value was chosen such that the simulation gave adoption rates across all heat pumps similar to DECC's prediction when $\boldsymbol{w}_{hassle}$ and $\boldsymbol{w}_{\mathrm{social}}$ were set to zero.

3. Results

Experiments were conducted altering the balance of the weights given by household agents to the factors. Firstly the sensitivity to the economic factor was explored using the runs summarised in Table 1. Each parameter setting was run 10 times with different random seeds due to the stochastic nature of the simulation. Results for each run were plotted, along with the ensemble average – an example is given in Figure 4

<Table 1 here>

<Figs 4A and 4B here>

Combining results over ensembles of runs, we plot the mean number of adoptions at 3 years (i.e. the endpoint of the bold blue line in Figure across all 13 ensembles) varying as a function of $\boldsymbol{w}_{hassle}$ (Figure 5). The data shown are for the ensembles described in Table 1 with a constant $\boldsymbol{w}_{social} = 0.5$, however the result is robust across values of $\boldsymbol{w}_{social}$.

<Figs 5A, B and C here>

4. Discussion

Firstly it is noticeable (Figure 4) that the model shows adoption reaching a plateau. In the runs with high rates of adoption (e.g. ensembles 1-6 from Table 1), this plateau is reached early in the simulation (within the first 3 years). With slower rates, the plateau is not reached until later. For high levels of $\boldsymbol{w}_{\mathrm{econ}}$ coupled with low levels of $\boldsymbol{w}_{hassle}$, adoption rates are high in general and GSHP adoption in particular is high. This is surprising as the high GSHP adoption in our simulation is due to the compelling nature of the purely economic case if no additional *hassle factor* is present; however lower rates were predicted in the economic analysis conducted by DECC. As $\boldsymbol{w}_{hassle}$ increases, the overall adoption remains high until $\boldsymbol{w}_{hassle}$ rises above 0.15 at which point the adoption drops off dramatically.

It should be noted that the economic factors in this model do already reflect the degree of *hassle* identified in the DECC impact assessment and supporting documents (DECC, 2013b; Enviros Consulting, 2008; Element Energy, 2008; Ipsos-Mori, 2013). However, the simulation results indicate that relatively low levels of additional hassle can lead to a tipping point at which take-up drops off dramatically (Figure 5). It therefore appears that adoption rates are highly susceptible to factors such as the heterogeneity of the adopting population and the process of decision making (including binary decision making such as that reflected in Figure 2), that are not purely economic and which are difficult to model other than with an ABM approach.

5. Conclusion and Policy Implications

It is noticeable that the current uptake of RHI for heat pumps is well below the run rate for new installations that prevailed prior to introduction of the policy, which was estimated by Delta (2012) to be in the region of about 4,000 GSHPs and 12,000 ASHPs per annum. The

DECC first year predictions of about 7,000 and 15,000 respectively therefore represent a modest acceleration that might reasonably be expected as a result of the incentive.

The modelling results presented here indicate that adoption is sensitive to non economic factors and there is a level of "*hassle factor*" above which uptake of heat pump technology falls away rapidly despite the existence of a robust economic incentive. Agent-based modelling has been shown to be useful in investigating these effects and may be of use in exploring the need for further policy interventions in this area, for example to facilitate energy service contracts that reduce the risk to the consumer from an unfamiliar technology, or to amend building regulations so that uptake is promoted.

Process (Green Deal assessment) and performance (heat emitter size) requirements have been added to the RHI but not included in its impact assessment. Although apparently modest when measured in cost and time relative to the installation and operating costs of any heating system, these seem to have added to the *hassle factor* sufficiently to take the policy into the unstable region identified in the modelling where uptake falls away sharply. The implication of this is that policy objectives are not being met.

This outcome raises the question of whether or how policy change might mitigate these process disincentives. Homes that are properly insulated and heat emitters that are adequate for good heat pump CoPs are clearly essential requirements for delivery of the carbon reduction goals of the policy. However, the complex process and rules documented in the "Essential Guide to Applicants" (Ofgem 2014) may well deter potential adopters of heat pumps at a time when their existing heating system has failed. Predictability and speed in installation are highly desirable given the high proportion of new heating installations that are distress purchases. It is likely that consumers need a "one stop shop" – a supplier that can provide a package deal that will satisfy all the RHI requirements and quickly install the system for a completely predictable cost and timescale. To reduce the effect of barriers on consumers in order that policy goals are achieved, simplification of the installation and application process may be needed.

It may be that market forces will in time stimulate packaged and simplified offers to consumers that will allow RHI uptake to recover to the levels predicted by DECC, however it seems likely that further policy change in order to address some of the issues identified by this paper will be needed.

Acknowledgement

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References

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. Proc. Natl. Acad. Sci. U. S. A. 99, 7280–7287.

Delta Energy and Environment, 2012. 2050 pathways for domestic heat – final report. Available from: http://www.energynetworks.org/gas/futures/2050-pathways-for-domestic-heat.html

Department of Energy and Climate Change (DECC), 2013a. The Future of Heating: Meeting the challenge. Available from: https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge

Department of Energy and Climate Change (DECC), 2013b. Renewable Heat Incentive – Domestic Impact Assessment. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211978/Domestic_RHI_Impact_Assessment.pdf

Department of Energy and Climate Change (DECC), 2013c. Further details of the domestic renewable heat incentive. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263190/Domestic_budget_management_publication_-_Dec_2013.pdf

Department of Energy and Climate Change (DECC), 2013d. MCS 021 Heat emitter guide for domestic heat pumps. Available from: http://www.microgenerationcertification.org/images/MCS%20021%20-%20Heat%20Emitter%20Guide%20v1.0%202013.12.16.pdf

Department of Energy and Climate Change (DECC), 2013e. LSOA estimates of households not connected to the gas network. Available from: https://www.gov.uk/government/statistics/lsoa-estimates-of-households-not-connected-to-the-gas-network

Department of Energy and Climate Change (DECC), 2014a. New scheme offers cash incentive to households using renewable heating systems in their homes. Available from: https://www.gov.uk/government/news/new-scheme-offers-cash-incentive-to-households-using-renewable-heating-systems-in-their-homes

Department of Energy and Climate Change (DECC), 2014b. RHI and RHPP deployment data: November 2014. Available from: https://www.gov.uk/government/statistics/rhi-and-rhpp-deployment-data-november-2014

Energy Saving Trust, 2010. Getting warmer: a field trial of heat pumps. Available from: http://oro.open.ac.uk/31647/

Energy Saving Trust (EST), 2014. Renewable heat | Energy Saving Trust [WWW Document]. Available from: http://www.energysavingtrust.org.uk/domestic/content/renewable-heat (accessed 1.8.15).

Enviros Consulting, 2008. Barriers to Renewable Heat Part 2: Demand Side. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42958/1_20090501125239_e____3Part2FinalReportv10.pdf

Element Energy, 2008. The growth potential for Microgeneration in England, Wales and Scotland. Available from: http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file46003.pdf

European Union (EU), 2009. Renewable Energy Directive. Available from: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028

Gilbert, G.N., 2008. Agent-based models. Sage Publications, Inc, London.

Ipsos-Mori, 2013. Homeowners' willingness to take up more efficient heating systems. Available from:https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191541/More_efficient_heating_report_2204.pdf

Lee, T., Yao, R., Coker, P., 2014. An analysis of UK policies for domestic energy reduction using an agent based tool. Energy Policy 66, 267–279. doi:10.1016/j.enpol.2013.11.004

McFadden, 1974. Conditional Logit Analysis Of Qualitative Choice Behaviour. in P. Zarembka (ed.), Frontiers of Econometrics, New York, NY, Academic Press.

Ofgem, 2014, 2013. Domestic Renewable Heat Incentive – essential guide for applicants. Available from: https://www.ofgem.gov.uk/publications-and-updates/domestic-renewable-heat-incentive-essential-guide-applicants

Stephan, C., Sullivan, J., 2004. An agent-based hydrogen vehicle/infrastructure model, in: Evolutionary Computation, 2004. CEC2004. Congress on. IEEE, pp. 1774–1779.

Which?, 2014. Which? reveals the most reliable boiler brands [WWW Document]. Available from: http://www.which.co.uk/news/2014/09/which-reveals-the-most-reliable-boiler-brands-379112/ (accessed 1.8.15).

Figure captions:

Figure 1 Strategy for decarbonisation of domestic heating to 2050. Source: DECC (2013a)

Figure 2 Predicted cumulative installs of ASHP and GSHP attracting RHI (DECC 2013b)

Figure 3 Household agents' decision algorithm, triggered by heating failure perception, which is evaluated daily.

Figure 4A: Cumulative adoption of ASHP in simulation, plotted for zero hassle factor (ensemble 1)

Figure 4B: Cumulative adoption of GSHP in simulation, plotted for zero hassle factor (ensemble 1)

Figure 5A: Total heat pump adoption at 3 years into simulation against $\boldsymbol{w}_{hassle}$

Figure 5B: ASHP adoption at 3 years into simulation against $\boldsymbol{w}_{hassle}$

Figure 5C: GSHP adoption at 3 years into simulation against $\boldsymbol{w}_{hassle}$

Table captions:

Table 1 Weighting factors in agent-based model testing sensitivity to increased hassle

Table 1 Weighting factors in agent-based model testing sensitivity to increased hassle

Ensemble number	w_{econ}	w_{hassle}	w_{social}
1	1	0	0.5
2	1	0.01	0.5
3	1	0.025	0.5
4	1	0.05	0.5
5	1	0.075	0.5
6	1	0.1	0.5
7	1	0.125	0.5
8	1	0.15	0.5
9	1	0.175	0.5
10	1	0.2	0.5
11	1	0.3	0.5
12	1	0.5	0.5
13	1	1	0.5

Fig_1_strategic_framework_for_low_carbon_heat_in_buildings_DECC

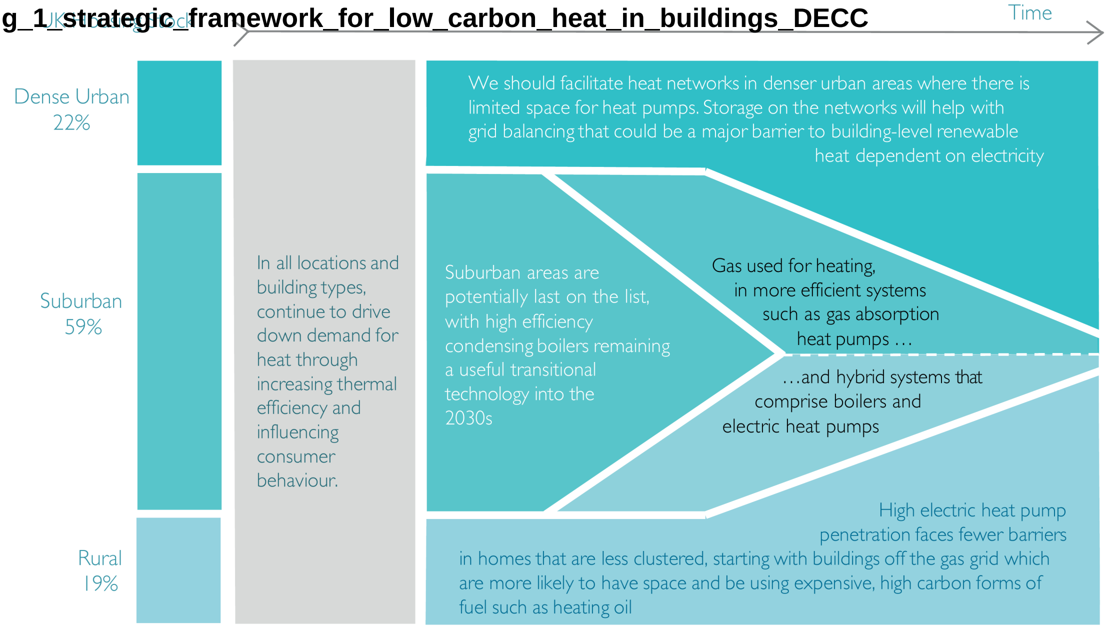

Fig_2_HP_expected_deployment

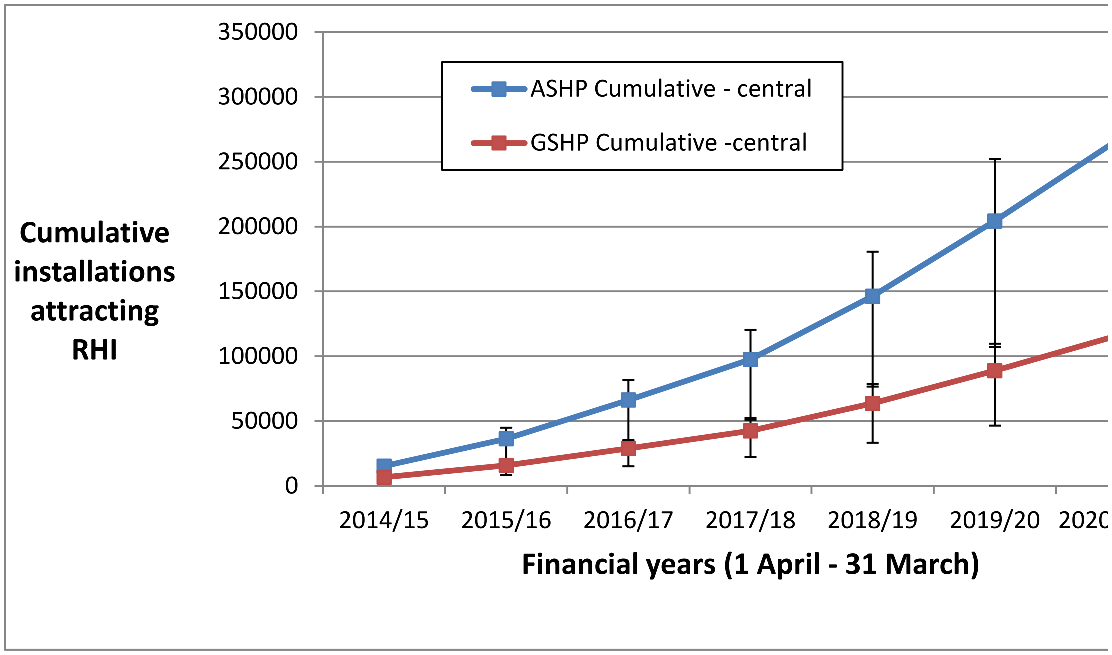

Fig_3_Household_agents_decision_algorithm

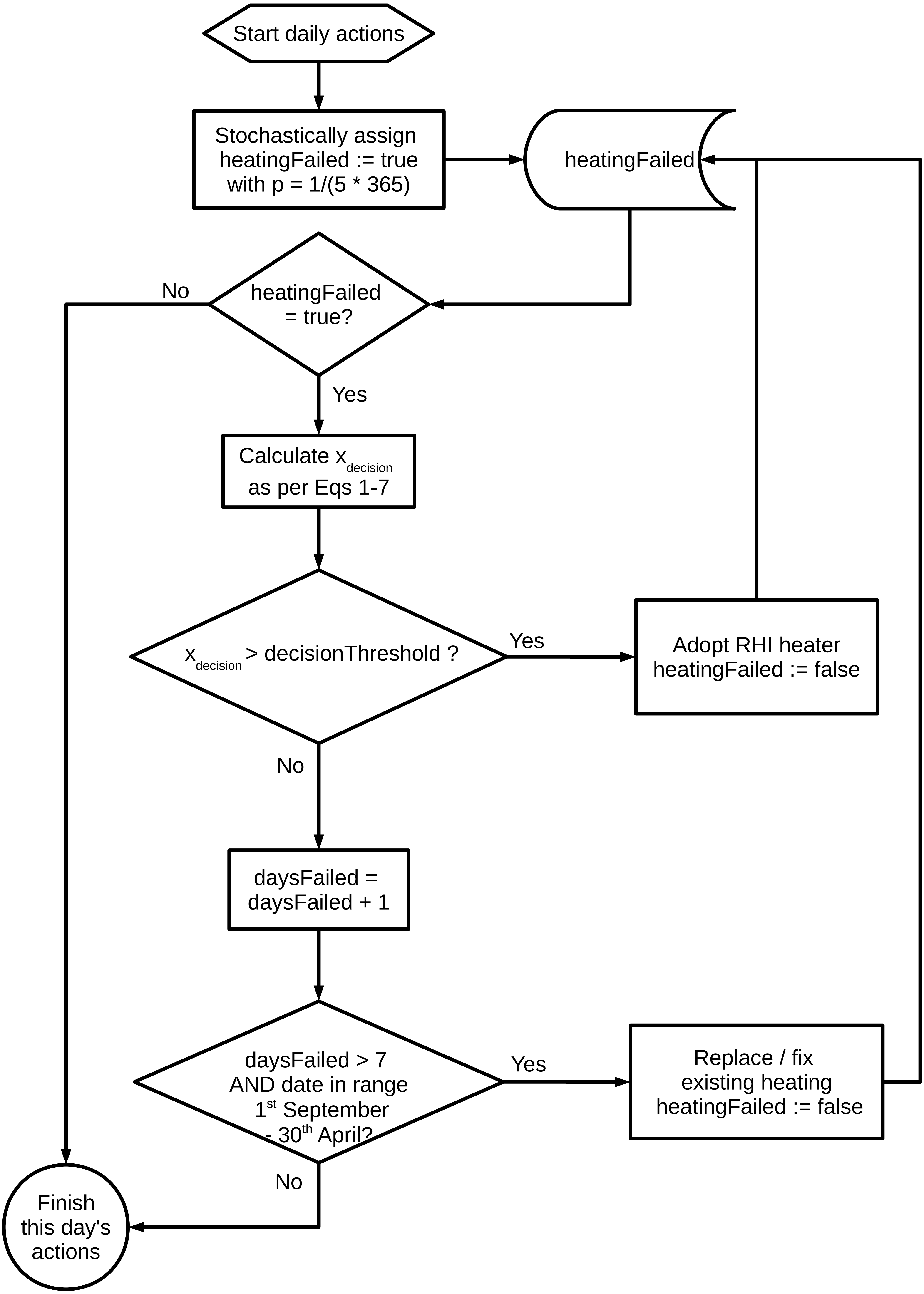

Fig_4A_ASHP_adoption_over_single_ensemble

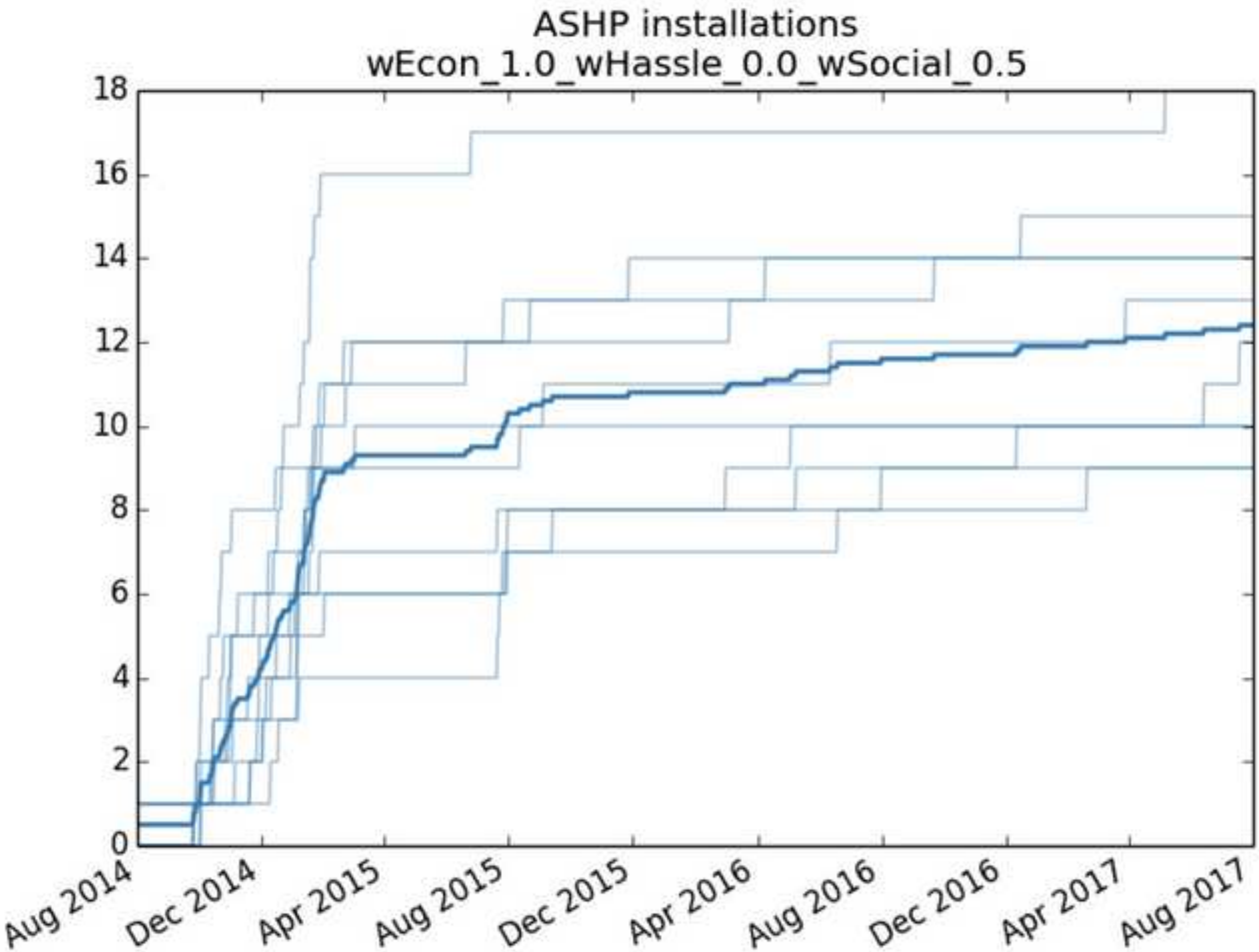

Fig_4B_GSHP_adoption_over_single_ensemble

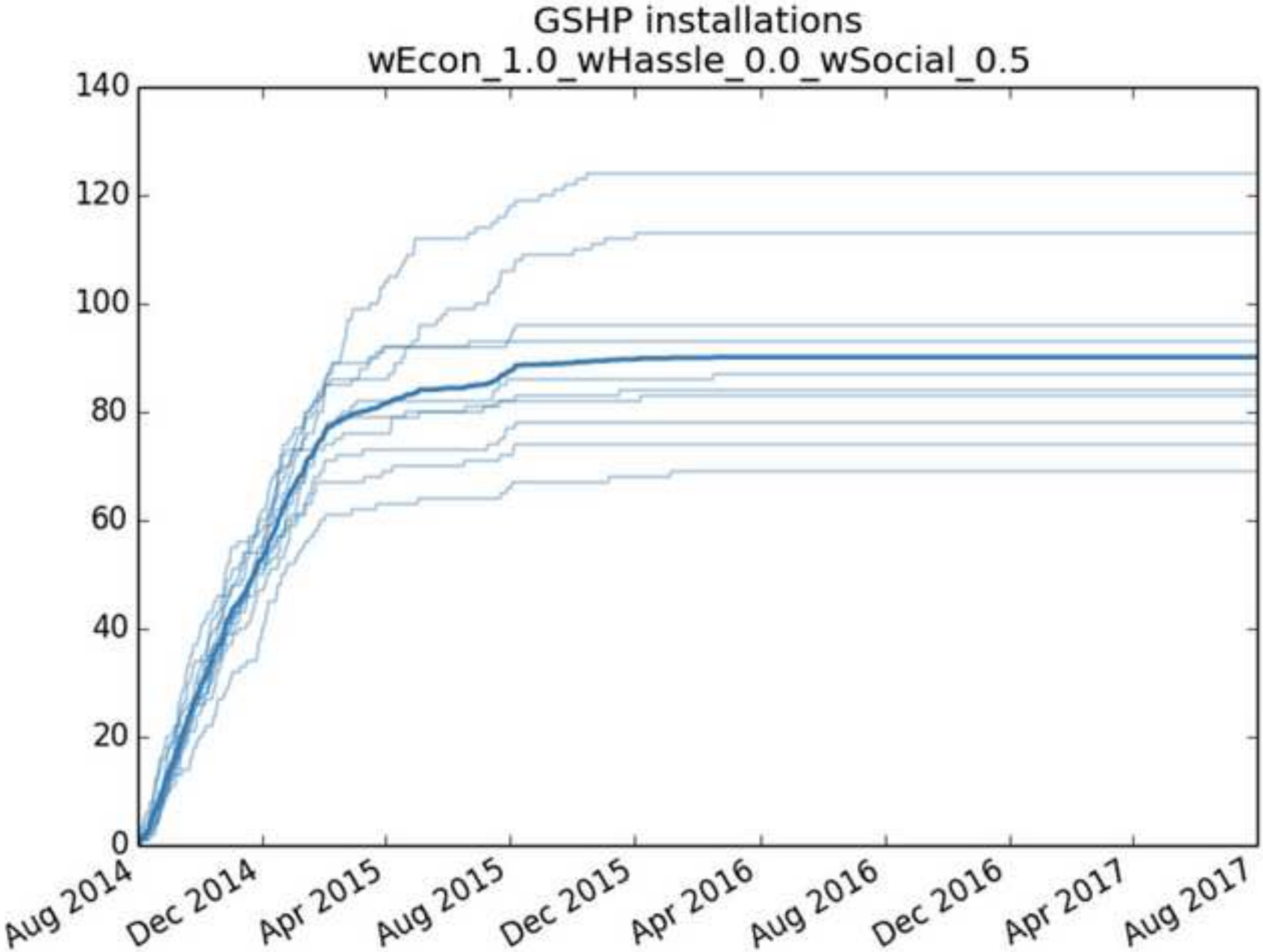

Fig 5A_Total_heat_pump_adoptions_wsocial_set_to_0.5

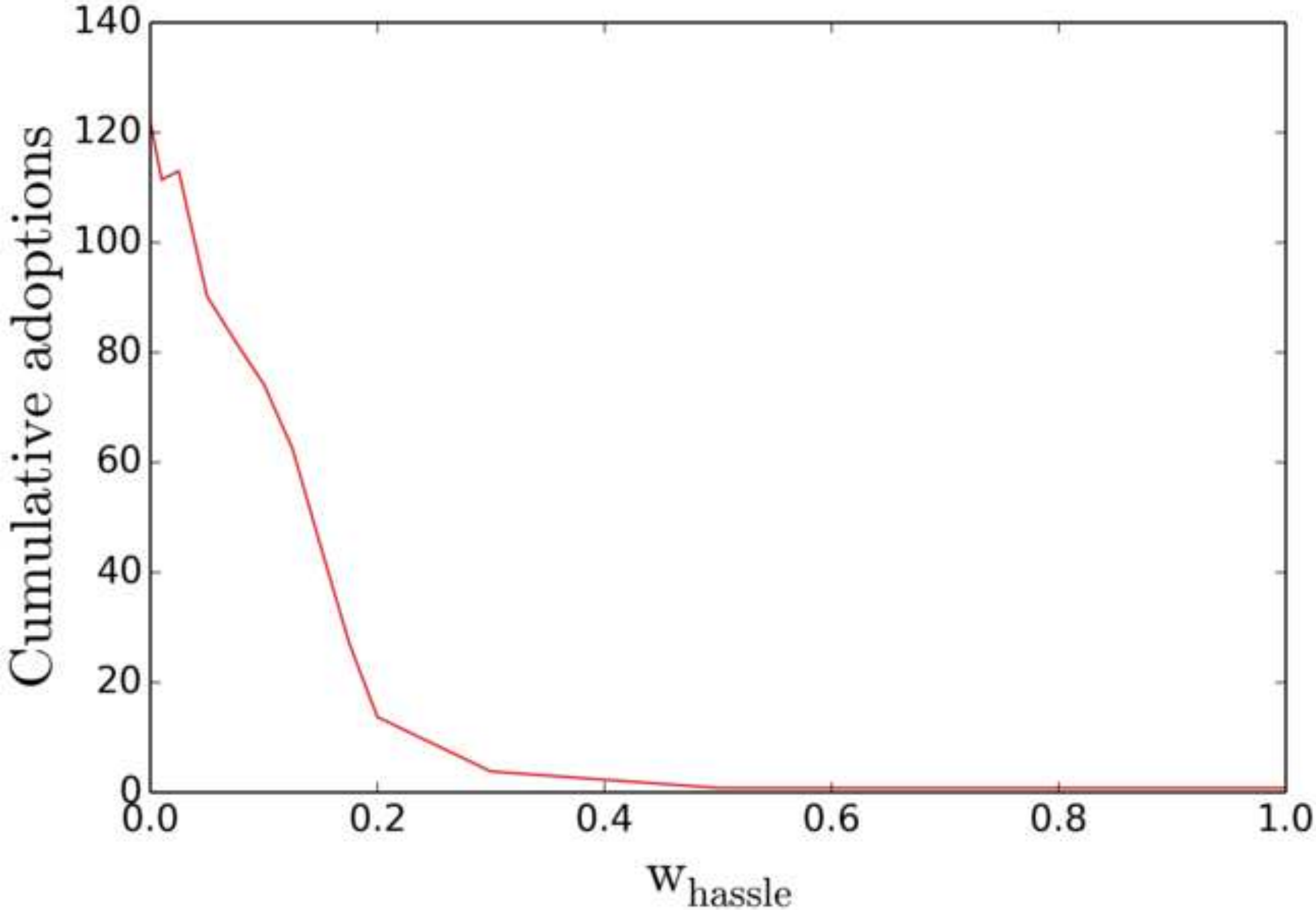

Fig 5B_ASHP_adoptions_wsocial_set_to_0.5

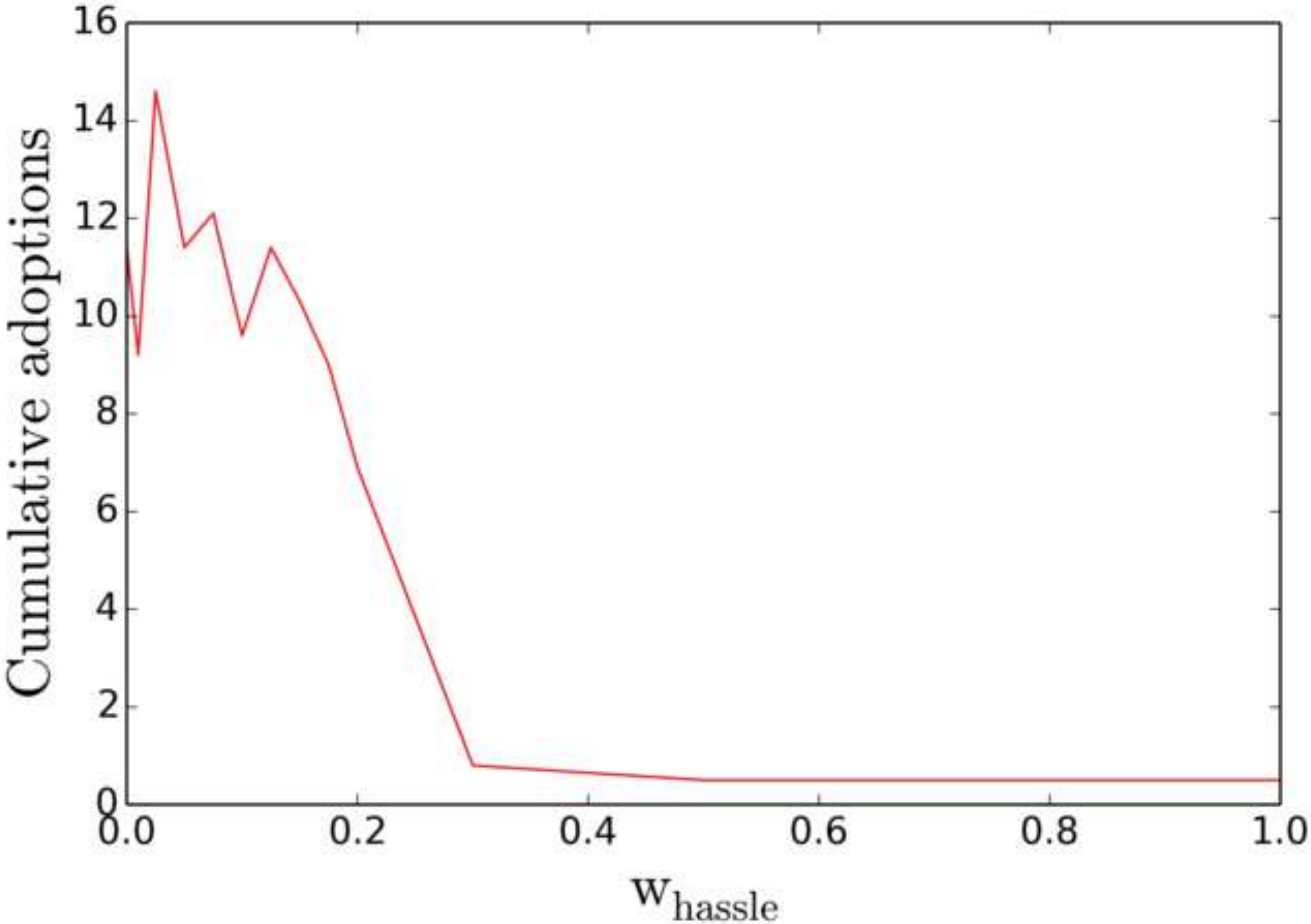

Fig 5C_GSHP_adoptions_wsocial_set_to_0.5