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Residential home heating: The potential for air source heat pump technologies as an alternative to solid and liquid fuels

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HIGHLIGHTS

- Air Source Heat Pumps can offer substantial savings over oil fired central heating.
- Significant residential air and climate emission reductions are possible.
- Associated health and environmental benefits are estimated up to €100m per annum.
- Results can inform policy interventions in the residential market to support change.

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ABSTRACT

International commitments on greenhouse gases, renewables and air quality warrant consideration of alternative residential heating technologies. The residential sector in Ireland accounts for approximately 25% of primary energy demand with roughly half of primary home heating fuelled by oil and 11% by solid fuels. Displacing oil and solid fuel usage with air source heat pump (ASHP) technology could offer household cost savings, reductions in emissions, and reduced health impacts. An economic analysis estimates that 60% of homes using oil, have the potential to deliver savings in the region of €600 per annum when considering both running and annualised capital costs. Scenario analysis estimates that a grant of €2400 could increase the potential market uptake of oil users by up to 17% points, whilst a higher oil price, similar to 2013, could further increase uptake from heating oil users by 24% points. Under a combined oil-price and grant scenario, CO_2 emissions reduce by over 4 million tonnes per annum and residential $PM_{2.5}$ and NO_X emissions from oil and peat reduce close to zero. Corresponding health and environmental benefits are estimated in the region of €100m per annum. Sensitivity analyses are presented assessing the impact of alternate discount rates and technology performance. This research confirms the potential for ASHP technology and identifies and informs policy design considerations with regard to oil price trends, access to capital, targeting of grants, and addressing transactions costs.

1. Introduction

Residential energy demand, and the associated choice of fuels and technologies, has implications for both greenhouse gases and emissions of particulate matter and other air pollutants. National and international commitments on greenhouse gases, renewables and air quality warrant greater consideration of alternative residential heating technologies. The residential market for final energy consumption accounted for 27% of final energy demand across all sectors in the EU28[1] in 2013. The scale of the residential energy demand market, as well as the number of individual agents involved, establishes it as an important and challenging sector to manage in respect of international environmental and energy policy.

Household energy demand is principally made up of energy requirements for space and water heating, as well as energy for appliances. The 2013 distribution of EU28 final energy consumption in households by fuel is shown in Fig. 1. Clearly fossil fuels continue to play a significant role in residential energy use. Research by Connolly et al. (2013) estimated that for the EU27 in 2010, the fuel type for almost three quarters of the total heat supply to residential and service sector buildings was comprised of natural gas (44%), petroleum products (17%), combustible renewables (10%) and coal products (3%). However, at an individual country level there can be substantial variation in the residential fuel mix.

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[1] Eurostat Online Data Code TSDPC320 – (Accessed 7th March 2016).

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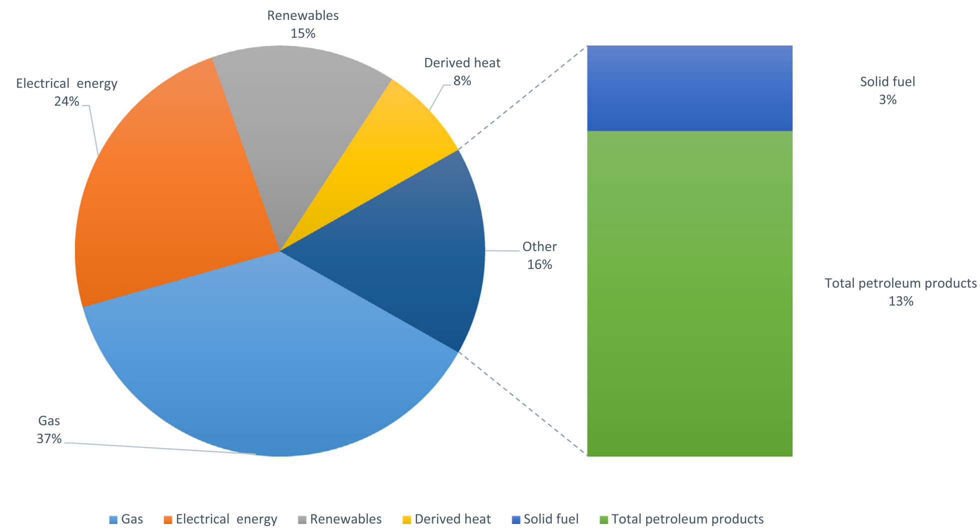

Fig. 1. EU 28 Final energy consumption in households by fuel in 2013. Source: Eurostat Online Data Code t2020_rk10.

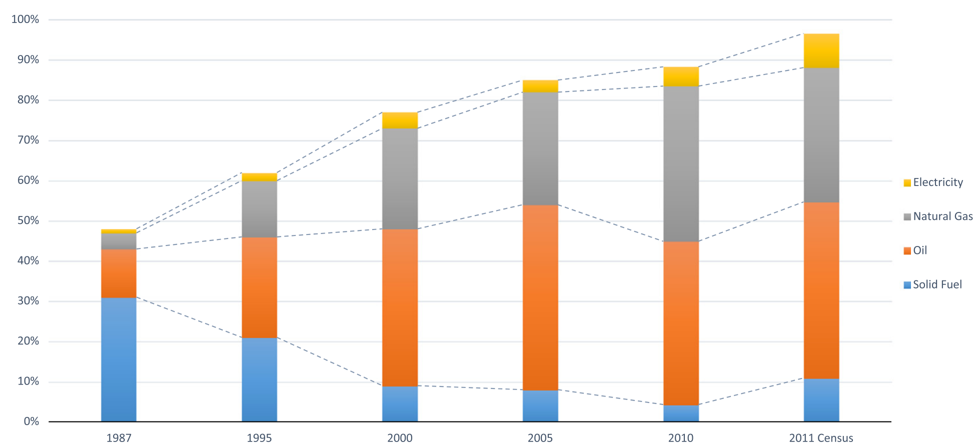

Fig. 2. Evolution of central heating by fuel type in Ireland from HBS surveys and census. Source: SEAI (2013) and CSO data.

Within Ireland there has been an interesting evolution of fuel choices in the residential sector over recent years as represented in Fig. 2. Historically, data on residential heating in Ireland has been gathered through a household budget survey,[2] which indicated a sharply falling trend in solid fuel use between 1987 and 2010, with the share dropping from 31–4.3%. Over the same period, the survey reported that the shares of oil fired and gas fired central heating grew substantially to 40.6% and 38.6% respectively. However, data from the Central Statistics Office Census of 2011 offers greater clarity on the nationwide statistics for residential heating, and suggests solid fuel was used by over 10% of households as their primary central heating fuel, with oil fired systems holding the largest market share at 43.8%.

Whilst specific fuel characteristics, combustion methods and technological factors will influence emission outcomes for the residential sector, data shown in Table 1 from the EMEP/EEA emission inventory guidebook 2013 show that solid fuel combustion at a household level will generally deliver substantially higher emissions of particulates and NO_X than oil or gas fired systems. These emissions are harmful to human health, and create challenges in relation to European air quality legislation, which is now driven by a focus on the reduction of negative health impacts (EC, 2013). Whilst electrified heating solutions generate no residential emissions at point of use, it is acknowledged that they may, of course, contribute to indirect emissions dependent on the source of electricity generation and the coefficient of performance (COP) of the electrified technology.[3] Nonetheless, there is an important distinction between the effects of household-level combustion of fuels, which emit pollutants at a low elevation often within more populated residential areas, and the effects of combustion in a

Table 1
Tier 1 residential combustion $PM_{2.5}$ and NO_X emission factors.Source: EMEP/EEA Emission Inventory Guidebook 2013 – Section 3.2.2.1 Residential Combustion (1. A.4.b).

Fuel type	$PM_{2.5}$ g/GJ	NO_X g/GJ
Coals (including hard and brown coal)	398	110
Gaseous Fuels (including natural gas)	1.2	51
'Other' Liquid Fuels (including oil)	1.9	51
Biomass	740	80

[2] http://www.cso.ie/en/statistics/housingandhouseholds/ (accessed 7th March 2016).

[3] The coefficient of performance in this context refers to the ratio of heating from a technology to the amount electrical energy utilised. The higher the COP the lower the operating cost.

Table 2
CO_2 Emission factors for selected residential fuels.Source: SEAI (2014).

Fuel type	g/CO_2 per kW h	g/CO_2 per kJ
Kerosene	257	0.071
Coal	341	0.095
Sod Peat	374	0.104
Peat Briquettes	356	0.099
Natural Gas	205	0.057
Electricity (2013 grid average CO_2 emissions in Ireland)	469	0.130
High Temperature Air Source Heat Pump with COP of 3	156	0.043

strongly-regulated power generation sector. In the latter case, emissions are monitored, managed and emitted generally from a higher elevation in a more industrialised zone. Whilst those power sector emissions may lead to broader regional transport and distribution of particulates and oxides of nitrogen, the existing Industrial Emissions Directive (Directive 2008/1/EC) in Europe and the general ambitions towards clean and renewable energy sources in Europe, as outlined in the EC roadmap for moving to a competitive low carbon economy in 2050 (EC, 2011), are expected inter alia to continue to further reduce the emissions associated with power generation across Europe in the coming years, thereby strengthening the case for electrification in sectors such as transport and residential.

Table 1 presents 'Tier 1' emission factors. The authors acknowledge that there is greater variation in emission factors where residential combustion is disaggregated into specific combustion technologies and individual fuel categories and qualities. However, in terms of residential home heating, given the level of detail in the available data for this study (i.e. census and building energy ratings which detail the general technology as opposed to specific technology and fuel use characteristics), a Tier 1 analysis was considered appropriate. In the future, more detailed studies may be possible through smart-metering data, detailed surveys and other innovations in the residential energy market.

CO_2 emission factors for selected residential fuels, as shown in Table 2, suggest that there may also be opportunities to further reduce carbon emissions from the sector through fuel-switching away from certain solid fuels. As alluded to previously, stated EC ambitions for further decarbonisation of the power grid into the future, coupled with efficiency improvements of electrified technologies, are expected to strengthen the environmental case for residential electrification for heating needs.

Within this context, the specific goals of this paper are to assess:

1. The comparative estimated performance of existing home-heating systems relative to air source heat pump technologies in Ireland with respect to emissions, investment and operational cost.
2. The potential market for air source heat pump technology in Ireland using an economic analysis under a number of defined scenarios.
3. The estimated CO_2, $PM_{2.5}$ and NO_X emission outcomes from those scenarios, and estimates of the health and environmental savings derived from associated emission reductions.

2. Literature

The motivation for abatement of particulates, NO_X and CO_2 is well established in the literature. NO_X is associated with human health impacts and environmental damage as an acidifying pollutant. Ambient particulate matter pollution has been identified as the main environmental cause of premature death in Europe (Lim et al., 2012). Indeed, recent comprehensive assessments have identified residential wood and coal combustion as important sources of particulates and consequent human health impacts in Europe and North America (UNECE, 2014). Despite this, Ireland and other European countries have seen increases in solid fuel use in the residential sector and a variety of factors play a role in these household choices (Fu et al., 2014). Indeed, European member states may now see stronger growth in biomass combustion at residential levels where this is encouraged under the aegis of European renewables policy.[4] Climate-inspired actions, such as the UK's 'Renewable Heat Incentive 2014' which, inter alia, encourage biomass burning for home heating as a sustainable and environmentally friendly choice for households, may lead to further negative impacts from air pollutants in residential areas (UNECE, 2014). $PM_{2.5}$ pollution in Ireland is currently estimated to account for over 700 premature deaths per annum (EnvEcon, 2015) as compared with Irish road deaths in 2011 which totalled 186 (Safety Road Authority, 2015). Air pollution health impacts do not attract the same media or public attention as an immediate and tragic road accident but, as a public policy priority, air pollution warrants sustained attention on the grounds of both meeting internationally legislated environmental targets and protecting citizen health.

The pressure to achieve reductions in global greenhouse gas emissions have been clearly and comprehensively assessed in the synthesis report of the IPCC Fifth Assessment Report (IPCC, 2014) and the need for ambitious action has been increasingly reflected in sequential iterations of European climate policy frameworks and legislation.[5] Within Ireland, the greenhouse gas targets established for those sectors outside of the European Union's emissions trading scheme, principally agriculture, transport and the residential sector, present national policy makers with a substantial challenge. These large, multi-agent sectors can be more difficult to manage than large point sources and, therefore, interventions and technologies which offer reduced emissions and a plausible economic case for action in these sectors should be of great interest to the policy system.

Electrification of home heating for the residential sector has the potential to reduce aggregate emissions of NO_X, CO_2 and particulates,[6] and this can deliver positive environmental outcomes as well as reduced human health impacts associated with poor air quality in residential areas. The general concept of residential heating electrification is to displace emissions from local-level fossil-fuel combustion with electrified technologies powered by well-regulated and increasingly clean and efficient power generation. It is a policy approach akin to policies that have been evaluated in the context of the electrification of the transport sector (Ayalon et al., 2013; Buekers et al., 2014). Indeed, Sugiyama (2012) references the early recognition of electrification by Manne and Richels (1992) as a means of achieving greenhouse gas emission reductions, including, specifically, their mention of the displacement of oil-fired residential heating with electric heat pump technologies. In his review of contemporary greenhouse gas mitigation studies, Sugiyama finds that the buildings sector offers

[4] Renewable Energy Directive 2009/28/EC.

[5] http://ec.europa.eu/clima/policies/2030/.

[6] And other air pollutants such as PAHs (e.g. Benzo[*a*]pyrene), which are recognised as toxic carcinogens and where emission factors for residential combustion are substantially higher for coals, biomass and oil than for gaseous fuels (EMEP/EEA, 2013). Residential solid-fuel combustion has also been recognised as an important source of black carbon (BC) emissions (UNECE, 2014). These other pollutants are not considered within the scope of this analysis.

the most potential for future electrification, and again references the role of heat pump technologies generally, along with an increasingly decarbonised power sector, as part of this potential.

In this same vein, a recent UK study, testing in a comparable climate to Ireland, found that ASHP technology offered the best tested solution for achieving a specified residential GHG emission reduction target (20%), as well as being the most credible financial option for application to the existing residential market (Rogers et al., 2015). It was noted that further technology improvements will improve the viability of the technology, whilst further reductions in the grid carbon intensity will also enhance the overall emission reduction potential. An earlier UK study which assessed large-scale future penetration of domestic heat pump technology in the UK similarly found that residential heat pump technology could offer a substantial contribution to the UK's long-term carbon emission reduction targets, particularly where paired with simultaneous decarbonisation of the power supply sector (Gupta and Irving, 2014).[7] It was further noted that current UK ambition and adoption rates fall far below what is required for meeting national emission targets, and therefore further policy interventions should be considered in the shorter-term.

Incumbent home heating technologies, however, can be expensive to replace and there can be an understandable inertia from householders with regard to shifting away from well-known technologies for home heating to a comparative newcomer to the mainstream home-heating market. Concerns surrounding installation and operational costs, as well as heating performance, can slow the market uptake to new technology. This paper focuses on Ireland and targets the primary space and water heating choices of the residential sector for a policy intervention designed around the displacement of more polluting oil and solid fuel residential combustion with ASHP technology. This paper undertakes an economic and environmental analysis for Irish households drawing on the latest technological data of one of the world's leading ASHP manufacturers, and detailed building energy rating data covering several hundred thousand homes. The paper goes further by considering the air pollutant outcomes of various scenarios, and quantifies associated environmental and health impact outcomes from a public policy perspective. The overall objective of the paper is to quantify the merits of such a technological policy intervention, to assess the potential market, and to provide robust policy decision support.

3. Methodology

The methodology employed in this paper seeks to analyse the current residential heating market in Ireland, the performance of various technologies in terms of efficiency and, finally, the economic and environmental cases for change. In this section the analytical approach is described.

A major component in the methodology for this paper is the Building Energy Rating (BER) dataset[8] managed by the Sustainable Energy Authority of Ireland. This database provides characteristics and detailed energy-consumption estimates of space heating, water heating, ventilation and lighting for all houses in Ireland that have obtained BER certificates. The BER dataset, as accessed in 2015, included 554,749 records representing 33.6% of all households in Ireland. As part of the initial filtering process the data set was stripped of all apartments and all homes with an existing heat pump technology. It is important to note that the reason for the exclusion of apartments was not because ASHP technology cannot be used in apartment buildings, indeed, centralised heat pump technology can be used to good effect in such cases and, in certain countries, equivalently sized air conditioning units can be commonplace in apartments. Rather, the issue is, that for an individual ASHP technology to be installed in an apartment in Ireland, it would require balcony space or installation through an external wall which is likely to require planning permission. This would add a new case-specific barrier and cost to the assessment. Similarly, whilst assessing a building retrofit with a large central heat pump would be possible, this would introduce a quite different technology profile and would entail a revised cost and benefit assessment. As such the authors opted to set aside apartments as a separate case for a future specific assessment of the potential and the specific opportunities and barriers in such cases. Beyond this, there was a standard data cleaning exercise which removed entries with null values. On completion of this process some 401,752 records remained.

The first stage of the analysis was to assess the energy consumption and energy costs of existing home heating systems. Specifically, delivered energy consumption of space heating (main and secondary), delivered energy consumption of mains-water heating, and the corresponding efficiency factors were key inputs for this estimation.[9] Energy consumption of main water heating was included as main water heating often shares the same appliance as main space heating. We assume that if an ASHP is used to replace an existing space heating device, that it will also be used for main water heating.

The BER offers an indication of the energy performance of assessed dwellings (SEAI, 2013, p59). However, actual energy use is understandably affected by the behaviour of the people who live in the dwellings, ambient temperature, desired indoor temperature, the period and spaces that are actually heated, and other individual factors of the dwellings that are not necessarily captured within the BER. For this study, the behaviour of people in each house and other individual factors outside of the BER database are not considered.[10] Desired indoor temperatures are set to 21 °C for living areas and 18° for other spaces, in line with BER assumptions. Estimated energy consumption values for the dwellings are adjusted to localised external temperature. Based on meteorological data and using ArcGIS, we have spatially allocated the degree days from the closest station to the individual dwellings and adjusted the energy consumption values of space heating with these temperature data, whilst keeping other factors constant. This was done to replace the average country values used in the BER dataset. Evidence from the heating degree day[11] data from meteorological stations in Ireland, shown in Fig. 3, indicates that

[7] In this paper the focus is specifically upon ASHP technology. However, we note that ground source heat pump (GSHP) technology generally offers a steady performance due to the more constant ground temperature, and indeed the literature shows that ASHP technology can struggle in extremely cold weather conditions (Safa et al., 2015). Nonetheless, in this case, as Ireland has a temperate climate, similar to the UK, the latest ASHP technology was identified as being well suited to the milder temperature and the lack of extremes. The reason for excluding GSHP technology is therefore not due to a lack of potential, but rather because it raises varied issues with regard to retrofit to a site (e.g. size, access, ground suitability) and the authors did not wish to deviate from the focus of the ASHP paper by incorporating another set of variable ranges (install cost, site suitability, performance factors) into this analysis.

[8] http://www.seai.ie/Your_Building/BER/.

[9] The delivered energy values in the BER data have considered the dimensions of the houses, ventilation, fabric heat loss, solar radiation, internal heat gained from lighting and the efficiency of heating appliances.

[10] Appropriate surveys of such detail are unavailable at present, though the gradual introduction of smart metering and smart home heating systems may well afford a valuable data set to support future studies.

[11] Heating degree days indicate the annual sum of numbers of those days that have a mean outdoor temperature below 15.5°, weighed by the corresponding absolute difference between the daily mean temperature and 15.5°. 15.5° is the base temperature that determines whether space heating is necessary (SEAI, 2013, p13).

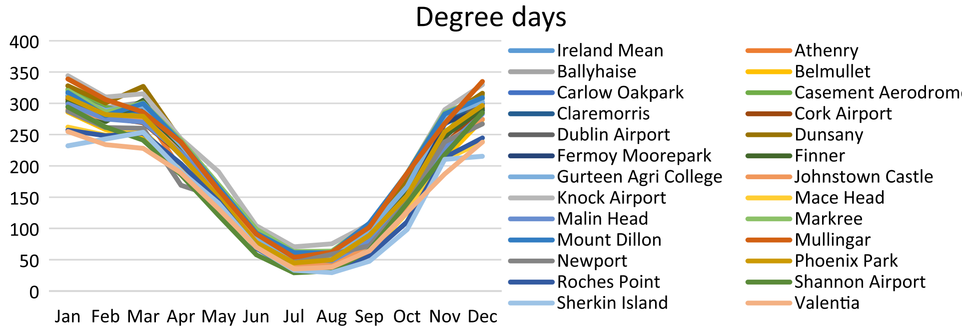

Fig. 3. Difference of degree days among meteorological stations. Data source: http://www.met.ie/climate/monthly-data.asp. Notes: Average values from 2012 to 2015.

the differences are reasonably large and merit recognition in this manner in the analysis.

In order to calculate the "new" energy consumption, where the existing heating system is replaced with an ASHP, some further analysis is required. Delivered energy consumption in the BER data considers the efficiencies of existing systems. However, those energy consumption estimates must be adjusted with the efficiencies of those existing systems (usually lower than 100% and which can be obtained from BER data directly) to estimate the actual heating energy needed for the dwelling. These estimated heating energy requirement values can then be applied to the efficiencies of the heat pumps.

The latest Seasonal Coefficient of Performance (SCOP) values of a specific brand of heat pumps in the market are used in our analysis. These are 390% for 8 kW heat pumps, 387% for 12 kW heat pumps and 376% for 16 kW heat pumps.[12] Energy consumption for existing main space heating (M), main water heating (W) and secondary space heating (S) correspond to the delivered energy consumption values from the BER data after the adjustment for local temperature, denoted as EM, EW and ES, respectively. The new energy consumption where air source heat pumps are deployed are calculated using the following equations,

$$PM_i = EM_i \times FM_i / H_{i,j} \tag{1}$$

$$PW_i = EW_i \times FW_i / H_{i,j} \tag{2}$$

$$PS_i = ES_i \times FS_i / H_{i,j} \tag{3}$$

PM, PW and PS represent the energy input required by heat pumps to generate the same heat as the existing heating systems in a given home. FM, FW and FS represent the efficiency factors of the existing system. In most cases FW and FM are equal as main water heating generally uses the same equipment as main space heating. However, we maintain them as independent values in the equation to allow for those less common cases where main space and water heating are powered by different systems. *H* represents the efficiency factors of the heat pumps. *i* indicates different houses and *j* denotes different sizes of heat pumps, i.e., 8 kW, 12 kW and 16 kW. The size of heat pump assigned to a specific dwelling is determined by the maximum heat required, calculated with the following equation,

$$HR_i = \left[(EM_i \times FM_i + ES_i \times FS_i) * \frac{21-(-3)}{T_I - (-3)} + EW_i \times FW_i \right] / 243/8 \tag{4}$$

HR is the heat required to keep the temperature at the desired high temperature (21°) and T_I is the average internal temperature. 21 °C is given as the specified internal temperature for living areas in the home (DEAP[13] manual, SEAI, 2012). Minus three degrees Celsius is assumed as the designed low ambient air temperature for heat pumps in Ireland. The annual values are divided by 243 and 8 to get hourly energy demanded, which is used to determine the appropriate size of the heat pumps for a given home. 243 represents the days of the heating season (October–May) and eight is the average number of heating hours per day. These are again the same figures as used in the calculation of delivered energy in the BER database (DEAP manual, SEAI, 2012).

To calculate the energy costs, Domestic Fuels Comparison of Energy Costs[14] data from 2015 are used. Although we have the energy consumption values of existing space and water heating systems, we must estimate the electricity and gas consumption for cooking and other non-heating appliances as electricity prices and gas prices are structured into bands on the basis of total consumption. BER data does not provide energy consumption data for cooking, fridges, wet appliances and other small appliances. Therefore, proportions of electricity consumption for these activities are obtained from the Energy in the Residential Sector report (SEAI, 2013, P46). We assume that proportions of electricity used for cooking can be applied to gas. The energy consumption associated with cooking, fridges, wet appliances and other small appliances are not used in the emission estimation calculations in this paper as they are not replaced by heat pumps. They are only used in regard to cost estimation as we need the total consumption of electricity and gas to allocate the households into the appropriate pricing bands. Comparative energy costs are then calculated based on the following equations,

$$CP_i = \sum_{j=1}^{n} \sum_{k_i=1}^{m_j} (PM_{i,j} + PW_{i,j} + PS_{i,j}) \times P_{j,k_i} \tag{5}$$

$$CE_i = \sum_{j=1}^{n} \sum_{k_i=1}^{m_j} (EM_{i,j} + EW_{i,j} + ES_{i,j}) \times P_{j,k_i} \tag{6}$$

CP is the running cost for heat pumps if they are used to replace the existing system in a dwelling and *CE* is the running cost for existing systems that can be replaced with heat pumps. $P_{j,ki}$ is the

[12] Data used in this study refers to a specific technology and has been provided from Glen Dimplex (http://www.dimplexrenewables.com). Performance values are at the leading edge of ASHP performance, and the seasonal performance factor calculations are based upon an outdoor design temperature of −3 °C and a system flow temperature for the heating system of 55 °C. This is the central scenario. Efficiencies for 65 C flow are 351%, 338% and 326% respectively. A sensitivity was run with the higher flow temperature to reflect the need for some older heating systems to have a higher flow temperature. Results are described in Section 6. Details of updated technology test results for a −10 design temperature and 55 C flow can be accessed at http://www.microgenerationcertification.org/ under the names A8M, A12M and A16M. Details of the installation process for the heat pumps are also available from Dimplex (Dimplex Renewables, 2014).

[13] Software used in BER assessment.

[14] http://www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/ - (accessed June 15th, 2016).

price of fuel j where consumption of fuel j is in band k_j. n is the number of energy types and m_j is the number of bands for energy type j. Bands are only used for gas and electricity. If the house i does not use fuel j for main space heating, then $EM_{i,j}=0$, similarly for $EW_{i,j}$ and $ES_{i,j}$. In Eq. (5), only j that represents electricity has non-zero values because heat pumps only use electricity.

Annualized capital costs of heat pumps are calculated with the following equation, which is derived from the equation of a geometric series.

$$A_s = \frac{C_s \times r \times (1+r)^L}{(1+r)^L - 1} \tag{7}$$

A is the annualized capital cost of heat pumps. C is the capital cost[15] of heat pumps. A/C is the capital recovery factor. s denotes the size of the heat pump. L is the life expectancy of the heat pump, which is set to 20 years. r indicates the discount rate of capital investment for heat pumps.

The choice of discount rate is somewhat controversial in studies of energy retrofits. We choose 5%, which is the current test discount rate for public sector projects in Ireland (Department of Public Expenditure, 2016). We choose this rate for our central scenario as this research is being carried out to inform Irish Government policy options regarding compliance with air and climate emission targets. It most likely will also be an input into decisions around grant-aiding of retrofit schemes. However, it is recognised that the cost of capital for private citizens will vary and so there is a difference between the appropriate discount rate for national policy studies and the discount rate that may need to be assumed when considering whether energy saving options will be taken up by private individuals and households. The 5% rate is similar to the current cost in Ireland of available products for extending mortgages for the purposes or retrofit (currently in the region of 4–5%). However, the cost of capital via a personal loan is likely to be in the region of 10% so we also calculated the results for this test discount rate. However, discount rates may also be higher as a result of factors causing what is known as the 'energy-efficiency gap' which inhibits the take-up of seemingly economically beneficial investments. Section 4 considers these barriers, and their effect on the discount rate, in greater detail.

Emissions are estimated with the following equations,

$$EP_t = \sum_{j=1}^{n}\sum_{i=1}^{h}(PM_{i,j} + PW_{i,j} + PS_{i,j}) \times EF_{j,t} \tag{8}$$

$$EE_t = \sum_{j=1}^{n}\sum_{i=1}^{h}(EM_{i,j} + EW_{i,j} + ES_{i,j}) \times EF_{j,t} \tag{9}$$

EF_j is the emission factor of energy type j, which are generally taken from EMEP/EEA emission inventory guidebook 2013. The exception is electricity, where the emission factors are calculated based on total electricity consumption data from the national Energy Balances 2013 (www.seai.ie) and emission data from power stations from the National Inventory 2013 (www.epa.ie). These are the most recent data available at the time of writing. Electricity is estimated differently because the emissions of electricity consumption are estimated here based on the power stations generating the household electricity. We transform the emission factors based on the fuels burned in the power stations to develop emission factors that correspond to the electricity used in the households. EP are the emissions if using heat pumps and EE are the emissions if using existing systems, t represents the types of pollutants that are estimated, and i denotes houses as per the previous equations. h is the number of houses. The relative reduction of energy consumption of fuels replaced by heat pumps and the relative increase of electricity demand used in heat pumps to replace those fuels are estimated based on BER data, then those relative changes are applied to the total stock of houses in Ireland to estimate the total national emissions. Therefore, the estimated emissions in this paper are representative not only the houses in the BER database, but all houses in the Republic of Ireland.

Table 3
Proportion of households that would return net positive savings from an ASHP.

Scenarios	*R only* (%)	*RC* (%)	*G+RC* (%)	*H+RC* (%)	*G+H+RC* (%)
Coal	99.73	44.72	61.96	45.48	62.41
Peat	100.00	82.82	91.98	82.91	92.07
Oil	99.89	62.31	79.46	86.13	94.53
LPG	96.96	49.36	62.65	72.94	82.87
Gas	99.67	39.52	57.07	41.30	58.36
Wood	96.40	55.07	67.06	55.51	67.57
Electricity	99.02	89.32	92.29	89.43	92.39

Notes: *R* means only comparing running cost between heap pumps and existing heating systems (capital cost of heat pumps is ignored). *RC* means considering running cost and capital cost of heat pumps. *G* includes a grant of €2422 and *H* indicates a high oil price scenario.

4. Potential market for heat pumps under assumed scenarios

The potential market for air source heat pumps in the residential market is examined here on the basis of an economic assessment. The presumption is that householders may purchase an ASHP if the costs are lower than the running costs of their existing heating system (sunk costs are excluded), whilst keeping the heat released from the old and new heating systems constant. Given that heat pumps are more efficient, it is immediately apparent that, when only considering running costs (i.e. ignoring the capital cost of an ASHP installation), heat pumps can be a viable replacement for most existing systems if the quotient of price of electricity divided by the price of existing fuels is less than the quotient of the efficiency of heat pumps divided by the efficiency of the existing system. Percentages in the column "R only" (running cost only) in Table 3 clearly support this argument. Percentages are under 100% for most fuels as the running costs of existing systems are affected by the efficiency of individual appliances and some households' use of mixed fuels. Beyond the R only scenario, the paper examines four other scenarios with regard to the market potential for ASHPs, as follows:

1. RC Running costs plus capital cost.
2. Grant+RC Running costs plus capital cost with a grant of €2400.
3. H+RC Running costs plus capital cost with a higher oil price.
4. G+H+RC Running costs plus capital cost with higher oil price and a grant of €2400.

Under the RC scenario, if the annualized running costs plus capital costs of heat pumps are lower than the running costs of the existing systems (capital costs of existing systems are excluded as they are deemed sunk costs), then households are included in the "potential market" for ASHPs. In other words, the move could be considered a viable economic decision. Currently, the capital costs of the 8 kW, 12 kW and 16 kW air source heat pumps are approximately €8700, €9300 and €9800, respectively. Capital costs are annualized using Eq. (7) before being added to the annual running costs.

[15] The capital costs include the heat pump system, A class cylinder, fittings, electrical and sundry items (e.g. heat pump base). It also includes 3 days of labour (electrical and plumbers) with overhead and VAT at 13.5%.

However, at this point, the authors acknowledge that, even where installation of heat pumps can save money, there are many reasons the market may not respond. There is a large literature exploring the barriers to the take up of energy efficiency measures which would appear to provide net benefits. As discussed in the prior section on discount rates, our central scenario uses a 5% discount rate; this is the recommended opportunity cost of public capital in Ireland (Department of Public Expenditure, 2016). However, if relying on private citizens to make the investment alone, the private discount rate is what is most relevant. At present, for those using finance from an extended mortgage product, the cost of borrowing is currently marginally lower than the 5% rate so our central scenario results hold up well in this case when simply considering the cost of capital. However, the cost of capital for those relying on a personal loan would be in the region of 8–12% and our sensitivity analysis (Section 6) using the 10% cost of capital shows that fewer households would benefit from the use of such funds for the investment. Fuel poor households generally rely on solid fuel and so they are potentially the greatest beneficiaries of this alternative technology. However, they are also likely to be less able to borrow the funds necessary to make such an investment and are likely to have discount rates that are multiples of the central scenario. Effectively this would be a total barrier to such an investment for many households. This is generally why such households are targeted for direct energy retrofits by state grant schemes, for example the Sustainable Energy Authority of Ireland Better Energy Warmer Homes Scheme.[16]

In addition to financial barriers, there are a number of other recognised barriers to the take up of seemingly economically beneficial energy investments. These comprise market failures such as information asymmetries, transactions costs and the non-internalising of externalities (Clinch and Healy, 2000; Clinch, 2005). Essentially, the costs of finding out about the energy retrofit options available, choosing between them, understanding the household's current energy consumption and calculating the private benefits are significant, and can all be a barrier to the take up of such measures. Such failures add to the other transactions costs such as searching for, and engaging, building energy rating experts and an installer, and suffering the inconvenience that having building works carried out on your property entails. Added to this are principal agent problems such as when the person responsible, or with the authority, to undertake the retrofit is not the person who will benefit, for example, in the landlord-tenant relationship. Gillingham and Palmer (2014) refer to one further market failure whereby early adopters absorb further costs in terms of ironing out issues with the new technology albeit that early adopters may benefit from the utility of being an early adopter. These authors also cite several additional reasons for the energy efficiency gap:

- Hidden costs: these include the administrative costs, as discussed above, but also that some measures may result in quality limitations (the authors cite less bright energy-efficiency light bulbs as an example).
- Consumer heterogeneity: in any large scale study, like the one in this paper, we effectively use the idea of an average consumer, whereas, in addition to the varying discount rates as discussed earlier, consumers will have different preferences.
- Uncertainty: estimating the benefits of energy retrofits is difficult enough for the householder but made more difficult by uncertainty surrounding whether the technology will actually deliver as described by the manufacturer (which can depend on the quality of the installer and the backup service) but, also, there is uncertainty about the parameters of the energy benefits, for example, as a result of fluctuations in energy prices.
- Overestimation of energy savings: models often underestimate the interactions between different energy investments.
- Rebound Effect: Certain model results tend to assume the energy service demand is the same before and after a retrofit which is not always the case, for example, comfort benefits being prioritised over energy savings.[17]

More recent research has turned to behavioural economics for further causes of the energy efficiency gap. Gillingham and Palmer (2014) provide a summary as follows:

- Non-standard preferences stemming from self-control problems which affect discount rates and reference-dependent preferences from such issues as loss-aversion, whereby consumers place a higher weighting on the potential risks of an energy retrofit not providing expected benefits.
- Non-standard beliefs regarding the costs and benefits of energy retrofits resulting from the limited ability of some consumers to assess all information and weight it appropriately, biases created in the framing of choices and sub-optimal decision heuristics, that is to say, applying inaccurate 'rules of thumb' when making investment decisions.

Ideally, these barriers to the uptake of seemingly financially-beneficial measures would be included in any financial analysis of the decision of the household to invest. This is extremely difficult to assess and beyond the scope of this paper. An alternative is to modify the discount rate to reflect these barriers. However, as explained by Gillingham and Palmer (2014), after 30 years of research on the issue of the energy gap, its size remains unresolved. The best-known energy and environmental models utilise several test discount rates and some, such as the PRIMES model, use private, sector specific discount rates (Cambridge Econometrics, 2015).

The lack of uptake of many, seemingly beneficial measures (even at a relatively high private cost of capital rate such as our 10% test rate), suggests that such discount rates could be in the region of 20–30% or more, reflecting a form of 'hurdle rate' which is additional to the cost of capital. Studies have shown that, for companies, such a rate could add 5% points to the cost of capital (Oxera, 2011). However, the cost to private individuals would likely be higher.

If a rate such as 30% were to be applied to our case, the results change dramatically. Therefore, in interpreting our results, the benefits as presented at our central scenario discount rate of 5% should be seen as being from the State's perspective or from the perspective of a highly-informed citizen borrowing at current mortgage rates. The 10% rate should be interpreted as a highly-informed individual borrowing in the market at personal loan rates. The 30% rate can be used to reflect a hurdle rate which builds into the discount rate these potential barriers to the take up of such measures. These scenarios are utilised in the sensitivity analysis in Section 6.

The objective of this paper is to provide a policy input, that is to say, to provide policymakers with an assessment of, effectively, what a social planner might see as an efficient policy intervention. The results show that from society's point of view, the retrofitting of heat pumps would, in many cases, be beneficial and would return more than a 5% rate of return. However, clearly, for such an intervention to be driven by the private market, there are a large number of barriers that would have to be overcome. This is evident from the fact that such measures have not been taken up and,

[16] http://www.seai.ie/Grants/Warmer_Homes_Scheme/.

[17] See Clinch and Healy (2003).

Table 4
Average savings from those households that return a net benefit from an ASHP replacement.

Scenarios	*R only*	*RC*		*G+RC*		*H+RC*		*G+H+RC*	
Average saving	**S running**	**S all**	**S running**	**S all**	**S running**	**S all**	**S running**	**S all**	**S running**
Coal	1046	1071	1813	927	1466	1073	1814	937	1475
Peat	1582	1055	1803	1136	1686	1074	1821	1153	1703
Oil	1035	619	1367	659	1208	863	1605	973	1517
LPG	1047	953	1697	924	1470	1158	1896	1202	1742
Gas	729	491	1226	504	1039	506	1240	523	1058
Wood	1209	1104	1853	1082	1633	1108	1856	1086	1637
Electricity	1784	1219	1936	1371	1894	1229	1946	1381	1904

Notes: S running means savings from the replacement when only considering running costs, i.e., capital cost of heap pump is ignored. S all means saving from the replacement when considering running cost and capital cost of heat pump.
Unit: Euro per annum.

Table 5
Average savings when all households in a category of heating system replace with heap pumps.

Scenarios	*R only*	*RC*		*G+RC*		*H+RC*		*G+H+RC*	
Average saving	**S running**	**S all**	**S running**	**S all**	**S running**	**S all**	**S running**	**S all**	**S running**
Coal	1042	320	1042	514	1042	331	1053	525	1053
Peat	1582	841	1582	1036	1582	858	1599	1053	1599
Oil	1034	297	1034	492	1034	718	1455	913	1455
LPG	1013	285	1013	480	1013	768	1496	963	1496
Gas	726	7	726	201	726	26	746	221	746
Wood	1163	425	1163	620	1163	435	1173	630	1173
Electricity	1766	1048	1766	1242	1766	1059	1777	1253	1777

Notes: See Table 4.
Unit: Euro per annum.

indeed, this is an ongoing challenge to be taken up by the research community and policymakers.

From the perspective of state intervention, there are a number of approaches to addressing the energy efficiency gap, including information campaigns, public authority housing renovation strategies, pay as you save capital support schemes and direct grants. Among the defined scenarios in our study, two include a Government grant to subsidise the capital cost of an ASHP, specifically a lump sum capital grant of just over €2400. This was chosen as it is an equivalent value of the £1700 upfront grant for air source heat pumps available in Northern Ireland.[18] Two of the scenarios also use an alternative oil price. Given that current (2016) oil prices are low relative to prices observed over the last 10 years, a higher oil price scenario was examined. This scenario uses the higher average price from 2013 for heating oil and LPG (Liquid petroleum gas). This allows for the fact that oil prices, and household expectations for such prices, may change.

Table 3 indicates, at a 5% discount rate (a sensitivity analysis is conducted later in the paper), a net positive economic outcome is returned by large shares of households under a variety of scenarios. The RC scenario is the principal scenario, considering both running costs and capital costs, but without the intervention of the government subsidy nor the assumption of higher oil prices. From the RC column, we can see that gas is the least likely to be replaced by heat pumps. Households that currently use electricity present the strongest case for switching to heat pumps in the RC case, as the unit cost of electricity is close to three times the price of other fuels in Ireland. Those families utilising older electric heating devices (families already with heat pumps have been removed from our database), such as electric convectors, pay a high cost for electric heating as the efficiency of conventional electric heating appliances are lower than 100%, compared with 376–390% in the case of the heat pumps assessed. At the 5% discount rate, the introduction of the grant increases the percentages of potential market uptake by 17% points (compared with RC) for oil users. The higher oil price adjustment further increases the potential uptake of heat pumps for existing heating oil and LPG users by 24% points (compared with *RC*). The *G+H+RC* scenario indicates the largest potential market shares for ASHPs by combining the effects of the higher oil price with the grant. With regard to the effect of oil prices, it is worth recalling the underlying size of the specific fuel shares in the residential heating market (Fig. 2) where, once again, we note oil as the major source of home heating at approximately 40% of the market, whilst solid fuels account for just over 10%.

Table 4 presents the average savings from those households that would return a net positive benefit from the replacement of their existing system with an ASHP. 'S running' in the table represents the savings from running costs (running costs of existing systems minus the running costs of heat pumps) with capital costs excluded. 'S all' includes the running costs of existing systems (sunk capital costs of existing systems are excluded) minus the sum of running costs and capital costs of heat pumps. Houses of different size and with varied energy performance ratings can differ significantly in terms of the economic outcomes. In simple terms, a small and highly energy-efficient building will not save as much as a larger less efficient building. Nonetheless, those households that return benefits from an ASHP could return savings of roughly €500 to €1200 per annum under the *RC* scenario when considering capital and running costs. In summary, on the basis of this analysis, there is an economic case for ASHPs in a large number of homes. However, it is again noted that these estimations are based on energy consumption as estimated from BER data. The BER methodology assumes that living areas are heated to 21 degrees and other spaces are heated to 18° for 8 h per day during a heating season defined as being between October and

[18] http://www.nidirect.gov.uk/domestic-rhi-payments.

Table 6
Energy consumption of different scenarios and required electricity for the replacement.

TJ	Energy consumption				Electricity used for replacement		
	BC	RC w/o gas	G+H+RC w/o gas	Rpl solid and oil	RC w/o gas	G+H+RC w/o gas	Rpl solid and oil
Coal	10,018	4559	2256	0	622	886	1146
Peat	8092	2154	822	0	650	781	861
Oil	34,690	9356	844	0	4937	6541	6708
LPG	1371	421	94	1371	117	167	0
Gas	20,797	20,797	20,797	20,797	0	0	0
Wood	1018	341	154	0	87	112	137
Electricity	9157	8086	9893	10,193	−7486	−7754	−7818
Sum	85,145	45,715	34,862	32,362	−1071	735	1035

Unit: TJ.

May. As people may turn off heaters, may not heat their houses to the required temperatures, may just heat single rooms, or may operate a shorter heating season there are a number of variables which may be refined on a case-specific basis. At present, it is likely that these presented savings are in the upper band of the range. However, in time, greater evidence in relation to individual households and behaviour will enable refinement of this analysis.

Table 5 gives the savings from the total replacement of an existing fuel heating system with ASHPs. The values in Table 5 are lower than Table 4 as households with negative returns from the replacement are incorporated into the averaging. Table 5 is included as it may be relevant for policies such as an outright ban on a particular fuel. It offers some insight as to the outcome where a given fuel is entirely replaced but, also, the results offer some support for policymakers to instead focus on more efficient, targeted policy interventions which encourage changes in specific locations, to specific types of houses, with specific BER grades.

5. Changes in energy consumption and emissions

The environmental implications of the heat pump scenarios are assessed by comparing the energy consumption and emissions before and after the displacement of existing heating technologies with the market potential of ASHPs as estimated in Table 3. Four scenarios are used in this comparison. BC stands for base case which represents the existing energy consumption and emissions from home heating. 'RC w/o gas' corresponds to the RC scenario in Section 4, which considers running costs plus capital costs. '*G*+*H*+*RC w/o gas*' is similar to the *G*+*H*+*RC* scenario, and includes the impacts from grants and higher oil prices. The only difference is that in w/o gas scenarios, gas is kept constant as gas is unlikely to be replaced by heat pumps. 'Rpl solid and oil' is a scenario in which all solid fuels and heating oil are replaced with heat pumps. Table 6 presents the estimated energy consumption outcomes of these four scenarios and the additional electricity used to replace the existing fuel systems.

In scenarios 'RC w/o gas' and '*G*+*H*+*RC w/o gas*', energy consumption of solid fuels, oil and LPG are significantly reduced. The replacement of these fuels demands more electricity from the grid, but this could be compensated for by the electricity savings that would accrue from those families who already use electricity for heating, upgrading their system to heat pump technology. The compensation is so large in 'RC w/o gas' that the final demand for electricity actually decreases by some 1071 TJ. In 'Rpl solid and oil', when all solid fuels and heating oil are replaced with heat pumps, this creates a large additional demand for the grid of 8854 TJ. However, the compensation from the replacement of conventional electricity heating systems is also large at 7818 TJ, and this can significantly reduce the additional burden on the power generation sector. As such, the gradual replacement of existing fuels should be accompanied by the gradual upgrading of conventional

Table 7
NO_X emissions for different scenarios and changes compared with the base case.

Tonnes	BC	RC w/o gas	G+H+RC w/o gas	Rpl solid and oil	RC w/o gas %	G+H+RC w/o gas %	Rpl solid and oil %
Coal	1102	502	248	0	−54	−77	−100
Peat	890	237	91	0	−73	−90	−100
Oil	1769	477	43	0	−73	−98	−100
LPG	58	18	4	58	−69	−93	0
Gas	874	874	874	874	0	0	0
Wood	82	27	12	0	−67	−85	−100
Electricity	990	874	1070	1102	−12	8	11
Sum	5764	3008	2341	2033	−48	−59	−65

Unit: Tonnes.

Table 8
$PM_{2.5}$ emissions for different scenarios and changes compared with the base case.

Tonnes	BC	RC w/o gas	G+H+RC w/o gas	Rpl solid and oil	RC w/o gas %	G+H+RC w/o gas %	Rpl solid and oil %
Coal	3987	1815	898	0	−54	−77	−100
Peat	3221	858	327	0	−73	−90	−100
Oil	66	18	2	0	−73	−98	−100
LPG	–	–	–	–	–	–	–
Gas	4	4	4	4	0	0	0
Wood	754	252	114	0	−67	−85	−100
Electricity	44	38	47	48	−12	8	11
Sum	8075	2985	1392	53	−63	−83	−99

Unit: Tonnes.

Table 9
CO_2 emissions for different scenarios and changes compared with the base case.

K Tonnes	BC	RC w/o gas	G+H+RC w/o gas	Rpl solid and oil	RC w/o gas %	G+H+RC w/o gas %	Rpl solid and oil %
Coal	1005	457	226	0	−54	−77	−100
Peat	845	225	86	0	−73	−90	−100
Oil	2621	707	64	0	−73	−98	−100
LPG	88	27	6	88	−69	−93	0
Gas	1173	1173	1173	1173	0	0	0
Wood	7	2	1	0	−67	−85	−100
Electricity	1328	1173	1435	1478	−12	8	11
Sum	7066	3764	2991	2739	−47	−58	−61

Unit: K Tonnes.

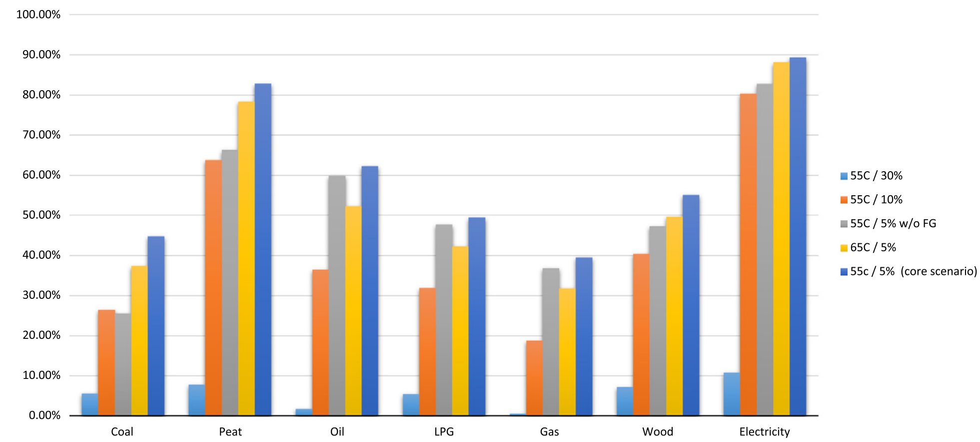

Fig. 4. Sensitivity analysis of the changes in the proportions of households in a given fuel category returning net savings from retrofit.

electric heating appliances to heat pumps, or other measures, to curtail excessive additional demand from the grid in the event of such a transition.

The changes of NO_X, $PM_{2.5}$ and CO_2 emissions before and after the replacements are shown in Tables 7–9, respectively. Percentage changes between 'RC w/o gas' and BC, '*G+H+RC w/o gas*' and BC and 'Rpl solid & oil' and BC are also presented in those tables. Significant reductions for all solid fuels, oil and LPG can be found in those tables for all pollutants and CO_2. Even under 'RC w/o gas' the annual reductions in NO_X and $PM_{2.5}$ emissions where mainly coal, oil, LPG, peat and wood are replaced, are substantial at 2.76 kt and 5.09 kt respectively. Coal, peat and wood are particularly significant in regard to $PM_{2.5}$ emissions, accounting for 98% of the estimated 5.09 kt reduction that might be achieved. These reductions carry particular weight when considering the health and environmental impacts discussed in Section 7. In terms of CO_2, coal and peat displacement under 'RC w/o gas' can offer over 1.17 million tonnes of CO_2 reductions, however, oil is the more relevant in this context offering reductions of approximately 1.91 million tonnes. All these estimates are based on BER energy consumption data and tier 1 emission factors. As such they should be considered as upper-band estimates in the absence of more detailed sectoral evidence. The ranges for what emission reductions might be achieved under the grant and high oil price scenarios are also included in the tables and indicate the full potential of emission reductions in those cases.

6. Sensitivity analysis

Our central scenario considers a flow temperature of 55 °C and a discount rate of 5% (the government test discount rate). We allow these coefficients vary to a flow temperature of 65 °C (SCOPs will decrease), discount rates of 10% (cost of a personal loan) and 30% (to include barriers to the take up of such measures as discussed previously) and we also examine the exclusion of those houses having a BER higher than F (i.e. F and G are excluded). Five combinations of sensitivity are shown in this section to demonstrate the variation of key results where these inputs are changed. The RC scenario is used as the base for these sensitivity runs. Fig. 4 presents the changes in the proportions of households that would be predicted to achieve a positive net saving from the adoption of the new technology under each assumption. The scenarios indicate the flow temperature (55 C or 65 C), the discount rate (5%, 10%, 30%) and the case where F and G are excluded (w/o FG).

The results show that, for the main target fuel areas of oil and solid fuels, the results are reasonably resilient where the 65 C flow temperature values are used. The proportions of homes that can

Table 10
Marginal damage values for air pollutants.

National estimate of marginal damage value per tonne of pollutant (€$_{2010}$ per tonne per annum)		
	NO_X Incl. Secondary PM	$PM_{2.5}$ Primary PM only
Ireland Rural	€925	€6,600
Urban Small (Pop 10,000–15,000)	€1,375	€14,800

Table 11
Net estimated changes in annual health and environmental impacts versus the base case scenario.

Difference in impact costs versus BC (€$_{2010}$)	*RC w/o gas*	*G+H+RC w/o gas*	*Rpl solid and oil*
NO_X Power Sector	107,115	(73,630)	(103,600)
NO_X Residential Sector	3,629,725	4,815,800	5,283,850
$PM_{2.5}$ Power Sector	33,660	(22,440)	(32,142)
$PM_{2.5}$ Residential Sector	75,263,920	98,958,720	118,805,076
Sum Total	79,034,420	103,678,450	123,953,184

achieve net savings from those fuel categories falls by up to 10% points. The exclusion of FG homes is not particularly relevant in the case of oil, but it is notable that, in the homes relying on solid fuels, the exclusion of such older homes has a more substantial impact on the share of homes that would benefit. It is likely, therefore, that more of the homes relying on solid fuels for their heating are in need of insulation and/or heating system upgrades. In regard to discount rates, the 10% rate does diminish the potential shares notably, but not to the point where the potential becomes lacking in importance. For example, over 35% of oil fired homes would still generate net positive returns at that discount rate. Those remaining homes would see their savings fall roughly 5%, but these would still be in the €600 per annum region. However, we then see that, at a higher discount rate of 30%, the share of homes that would see a net benefit from the ASHP investment in the key categories of oil and solid fuel heating would drop substantially, to levels below 10% in all cases.

7. Estimated health and environmental Impacts

The marginal damage values for air pollutants guidebook for Ireland (EnvEcon, 2015) includes estimated values for the marginal damage associated with a tonne change in the levels of a given air pollutant. The guidebook distinguishes between rural and urban areas of different scale to allow for adjustments in expected exposure and impacts. This guidebook and these values have been applied to estimate health and environmental impacts for this study. In calculating the impact values the following have been used:

- Residential emission changes use the 'urban small' values from the guidebook.
- Power sector emission changes use the 'Ireland rural' values from the guidebook.

The reason for using the latter is to reflect that power sector emissions are generally emitted from a high elevation in a non-urban area. The relevant values from the guidebook are presented in Table 10.

Aggregating the emission reductions of the various scenarios we find that the range of emission reductions associated with scenarios 'RC w/o gas' to 'Rpl solid & oil' would be between 5.1 and 8 kt of $PM_{2.5}$, between 2.7 and 3.7 kt of NO_X and 3.3–4.3 million tonnes of CO_2. In Table 11, the health and environmental impact costs for these net emission changes from the residential and power sector are monetised using the aforementioned guidebook. CO_2 values are not monetised but can be considered at the reader's discretion in terms of international carbon market prices and outlooks.

8. Conclusion and policy Implications

This paper estimated the potential market for air source heat pumps on the basis of an economic analysis. We found that, for large shares of households, representing almost all types of heating systems, from a societal perspective, there is a likely economic justification for moving to ASHP technology when considering the annualized capital and running costs. Indeed, the analysis suggests that for some 60% of the oil fired heating systems users in Ireland, investing in ASHP technology could reap substantial savings in the region of €600 per annum.

A number of alternative scenarios were run to assess the influence of capital grants and a higher oil price on the potential market for ASHPs. The lump sum grant of €2400 can increase the potential uptake of heat pumps by oil users by 17% points, and a higher oil price, similar to oil prices in 2013, could increase the potential of switching for heating oil and LPG users by 24% points.

From a public policy perspective, there are also important benefits to be captured. The evaluated scenarios show that up to 8 kt of $PM_{2.5}$ and 3.7 kt of NO_X could be abated annually under the scenarios, as well as reductions in CO_2 emissions of approximately 4.3 million tonnes per annum. The health and environmental benefits associated with the air-pollutant reductions alone are estimated to be in the region of €80 m and €125 m per annum for the evaluated scenarios. These would push the internal rate of return of such investments to be well in excess of the 5% test discount rate.

Whilst the scenarios involving a higher oil price and a capital grant deliver a greater potential market for ASHP technology, the assessment of the possible market when just comparing the annualized capital and running costs of existing systems against ASHPs already suggests significant potential for change. Thus, whilst promoting ASHPs at a time of higher oil prices (or price expectations) and offering capital grants may stimulate greater market response, it would seem that there is already considerable potential, and good progress may be achieved by addressing two of the other presumed barriers to change, firstly, the absence of clear information for households by which they can assess the potential merits of the change and, secondly, the provision of innovative financial products to support access to the initial capital necessary for the investment. Nevertheless, our analysis shows assumptions about the discount rate also have significant impacts on the results. If private individuals bear the cost of the retrofit, depending on their financial scenario and the extent to which financial, market and behavioural barriers to investment persist, the proportion of households taking up the retrofit would likely be lower than the socially optimal rate. In particular, fuel poor households, who are most likely to be using solid fuel currently, are likely to require direct support through larger-scale schemes of retrofit. However, we believe that this paper shows that heat-pump technology provides a viable option for a proportion of such upgrades.

The paper also flags the importance of a targeted approach to grant aid. It is not advised to offer the grant to all users of a specific home heating system. Instead, we suggest targeting the grant system at homes where adequate savings are estimated (accounting for home size, location, building energy performance). This study allows such a determination to be readily made by policy makers.

In terms of future work, residential insulation and actual energy consumption behaviours of the householders have the potential to reduce energy demand for space and water heating and these policy options are particularly relevant to more accurate estimation of BER energy consumption and the economic case for ASHP technology in certain circumstances. Similarly, detailed information about household fuel use and technologies would enable refinement of the air pollutant emission factors beyond the tier 1 values utilised in this work.

Future studies may combine this analysis with a residential insulation policy programme and householder behaviour analysis to refine the targeting of policy actions (e.g. deep retrofit) to save households money and reduce environmental and health impacts associated with the residential sector. Ultimately the analysis clearly suggests that ASHPs can play an important role in managing residential emissions and reducing household energy costs now and into the future.

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Glossary

ASHP: Air Source Heat Pump;
BER: Building Energy Rating;
CO_2: Carbon Dioxide;
COP: Coefficient of Performance;
EPA: Environmental Protection Agency (of Ireland);
GHG: Greenhouse gas;
Gj: Gigajoule;
GSHP: Ground Source Heat Pump;
IPCC: Intergovernmental Panel on Climate Change;
Kt: Kiloton;
Kw: Kilowatt;
LPG: Liquefied Petroleum Gas;
NO_X: Oxides of Nitrogen;
$PM_{2.5}$: Particulate Matter of no greater than 2.5 μm;
SCOP: Seasonal Coefficient of Performance;
SEAI: Sustainable Energy Authority of Ireland;
SPF: Seasonal Performance Factor;
Tj: Terajoule;
UNECE: United Nations Economic Commission for Europe.