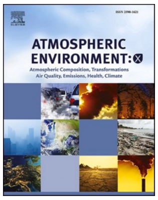
ATMOSPHERIC ENVIRONMENT: X 13 (2022) 100155

Contents lists available at ScienceDirect

Atmospheric Environment: X

journal homepage: www.journals.elsevier.com/atmospheric-environment-x



Hitting the hotspots – Targeted deployment of air source heat pump technology to deliver clean air communities and climate progress: A case study of Ireland

Eoin Ó Broin[a,b,d], J. Andrew Kelly[a,b,*], Gabriela Sousa Santos[c], Henrik Grythe[c], Tove Svendby[c], Sverre Solberg[c], Luke Kelleher[b], J. Peter Clinch[b]

[a] EnvEcon, 11 Priory Office Park, Blackrock, Dublin, A94 PH04, Ireland
[b] UCD Environmental Policy, University College Dublin, Belfield, Dublin, D04 V1W8, Ireland
[c] NILU - Norwegian Institute for Air Research, 2027-Kjeller, Norway
[d] Centre International de Recherche sur l'Environnement et le Développement (CIRED), 45 Avenue de la Belle Gabrielle, 94736 Nogent-sur-Marne Cedex, France

ARTICLE INFO

Keywords:
Residential sector
Space heating
Energy efficiency
Buildings
Energy
And climate policy
Carbon pricing
$PM_{2.5}$
Air source heat pump
Air pollutant

ABSTRACT

Electrification of residential heating and investment in building energy efficiency are central pillars of many national strategies to reduce carbon emissions from the built environment sector. Ireland has a strong dependence on oil use for central heating and a substantial share of homes still using solid fuels. The current national strategy calls for the retrofitting of 400,000 home heating systems with heat pumps by 2030, principally replacing oil fired heating systems. Displacing natural gas, oil and solid fuel boilers with heat pumps will have a favourable impact on climate outcomes. However, the impact on air pollutant outcomes is far more favourable when solid fuels are replaced, and the positive impact on ambient air quality is much enhanced where concentrated clusters of solid-fuel use are targeted. This research spatially analyses emissions and air pollutant concentration outcomes for both targeted and non-targeted deployments of heat pumps and shows that a focused deployment of just 3% of the national heat pump target on solid-fuel homes could offer similar progress on climate goals but with a substantial impact in terms of reducing air pollution hot spots. For the Irish residential heating season (October–March), the targeted solid fuel scenario delivers average $PM_{2.5}$ concentration decreases of 20–34%. This paper shows that these targeted communities are often in areas of relative deprivation, and as such, direct support for fabric retrofitting and heat pump technology installation offers the potential to simultaneously advance climate, air and just transition policy ambitions.

1. Introduction

Climate policy and air pollution policy are inextricably linked through the many common sources and activities that give rise to emissions of both. Occasionally, there are trade-offs between climate and air policy (Williams, 2012). However, more often than not, there are synergies (ApSimon et al., 2009). A sensible ambition for policymakers should be to harmonise and integrate actions across multiple political priorities such as climate change, air quality, just transition and other domains where possible. Such broad perspective policymaking is clearly articulated in the European Green Deal (EC, 2019) and broader global strategies such as the UN Sustainable Development Goals (UN, 2015). The European Green Deal includes commitments to reducing greenhouse gas emissions by at least 40 percent by 2030 as compared with 1990 levels while discussions are ongoing to increase this level of ambition to 55% as part of the EU goal to be climate-neutral by 2050 (EC, 2021). This builds from the earlier EU Roadmap to 2050 which committed to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050 (EC, 2011).

Despite these noble objectives, in the recent past, there have been failures in policy design that have resulted in a more narrowly focused ambition in one context contributing to adverse outcomes in another. In the transport sector, in many member states across Europe, the encouragement of vehicles with lower carbon emissions per kilometre saw strong growth in diesel vehicle numbers with clear knock-on impacts on diesel-fleet growth (Leinert et al., 2013). Diesel vehicles have

---

[*] Corresponding author. EnvEcon, 11 Priory Office Park, Blackrock, Dublin A94 PH04, Ireland.
E-mail address: Andrew.Kelly@ucd.ie (J.A. Kelly).

https://doi.org/10.1016/j.aeaoa.2022.100155
Received 22 September 2021; Received in revised form 13 January 2022; Accepted 31 January 2022

lower CO_2 emissions per kilometre than petrol vehicles, but higher emissions of particles and NO_X[1]. Moreover, a higher fraction of NO_2 is directly emitted, which is relevant to NO_2 air concentrations close to roads (Anttila et al., 2011; Casquero-Vera et al., 2019). This 'dieselisation' of the fleet has led to poorer air quality around Europe in highly trafficked areas (Hooftman et al., 2018). In the European Union in 2018, 95% of all NO_2 annual mean air concentrations that were above the corresponding limit value in the legislation (AQD, 2008) were observed at traffic stations (EEA, 2020). In a similar vein in the transport sector, EU biofuels policy (EC, 2009a) required that 10% of transport fuels should come from renewable sources by 2020 as part of the effort to reduce associated net climate emissions. This has typically been implemented with a 10% biofuel blend which has, in turn, proven controversial where it has incentivized indirect land use change (ILUC), e.g., where tropical rainforests in Indonesia have been cleared to plant palm trees whose oil is ideal for ethanol. In these cases, policymakers have subsequently reacted to address these conflicts (e.g., additionally recognising NO_x as part of vehicle taxation policies, and by recognising ILUC as an impact). However, legacy impacts are still apparent.

In the context of the built environment, there have been similar conflicts between climate and air policy. The 2010 EU mandated, National Renewable Action Plans to 2020 (EC, 2009b), set legally binding national targets for contributing to an EU-wide target of 20% renewable-sourced energy in Final Energy Demand by 2020. Related to this, biomass combustion in the residential heating sector has been promoted as a 'climate-friendly' policy (Monforti-Ferrario and Belis, 2018) and has since made up most of the sector's stated renewable energy use, despite the risk of adverse impacts on air pollution outcomes, and the questionable long-term climate neutrality of mass adoption of biomass burning (Cordell et al., 2016; Schulze et al., 2012). In detail, 19.5% of energy for heating and cooling across the EU in 2017 came from renewable sources, and 83% of this was from solid biomass (Enerdata, 2021). The linked directional effect on air pollutant emissions in the EU is upward pressure on NOx, PM_{10}, $PM_{2.5}$ and VOC,[2] and downward pressure on SO_2 (Capizzi et al., 2019).

The objective of this paper is to assess and discuss an opportunity for synergistic policy design across climate, air, health and just transition policy goals. In this case, it is not that the displacement of oil-fired heating systems with air source heat pump (ASHP) technology is harmful for air pollution outcomes and ambient air quality. Rather, it is that a climate focused policy, absent any spatially targeted refinements, foregoes the clear opportunity to reduce simultaneously national air-pollution emissions, and to remove, or reduce, relative hotspots of ambient air pollution in communities most affected by emissions to air from residential heating. ASHPs are a common element internationally in many contemporary residential retrofit strategies for climate policy, and with good reason. They offer an efficient, clean, economic, electrified form of home heating that is unconstrained by gas and fuel-delivery infrastructure. The ASHP coefficient of performance is such that approximately three units of heat are delivered to a building for every unit of electricity input. In our case country of Ireland such systems are quite suitable for the relatively mild Irish climate in which the number of days per year where temperatures are negative are limited (Met Éireann, 2022).[3] Paired with an increasingly decarbonised power sector, the technology therefore offers many advantages from a climate policy perspective. However, the focus of this research is not on the merits of the existing strategy to retrofit 400,000 ASHPs in Ireland. Instead, this paper seeks to highlight an opportunity for such international climate policy goals to refocus their policy design so as to simultaneously address multiple policy priorities across climate, air, health and a just transition. Specifically, through an evidence-based targeting of their deployment.

This paper is structured as follows. Section 2 offers a more detailed context for the case study as applied to the residential heating sector in Ireland. Section 3 describes the scenario design and analytical methodology, as well as the spatial assessment and modelling of emissions and air pollutant concentrations. Section 4 presents the results of the analysis, whilst Section 5 clearly defines the implications and recommendations for policy design. Section 6 concludes.

2. Context

The use of solid fuel for heating in the residential sector remains a relevant source of both carbon and air pollutant emissions in many countries. Solid fuel use has averaged 20% of total final energy demand in the residential sector across the EU between 2010 and 2018, albeit there is a substantial variation observed in the levels across individual member states, ranging from 46% in Poland to just 4% in the Netherlands. Fig. 1 presents the percentage shares of residential sector final energy demand for biomass and coal/peat for each of the 28 countries of the EU (EU28) in 2018. The levels of solid fuel use for the top six countries (Poland to Czechia) have been steady or rising to 2018 and this presents serious public-health concerns whilst also representing a substantial source of climate emissions. Biomass makes up the bulk of the solid fuel in most countries, with the exception of Poland, Czechia and Bulgaria, where coal use remains dominant. In our case country of Ireland, peat and coal are the main solid fuels used. Irish data for 2016 shows the share of solid fuel systems for residential heating (in particular coal and peat) were relatively high at 14% (SEAI, 2018).

In the EU28 in 2018, 54%, 41%, 44%, and 37% of the primary emissions for the pollutants $PM_{2.5}$, PM_{10}, CO and BC[4] respectively, resulted from energy use in the built environment (residential, commercial, and institutional) sector. This is also the sector with the lowest reductions in air pollutant emissions (with the exception of SOx[5]) since the year 2000 (EEA, 2020). The air pollutant with the highest impact in terms of premature deaths is $PM_{2.5}$. The European Environment Agency (EEA) has estimated 374,000 premature deaths in 2016 (EEA, 2019) and 379,000 in 2018 (EEA, 2020) for the EU28 due to long-term exposure to $PM_{2.5}$. There are also other broader negative impacts such as morbidity, productivity loss, and greater health expenditure, and these additional costs are expected to further increase with an ageing population. The health effects are not only on the respiratory and cardiovascular systems (Hoek et al., 2013; Holst et al., 2018; Raaschou-Nielsen et al., 2013), but also include neurological effects (Oudin et al., 2016, 2018) and even effects on birth weights (Olsson et al., 2020). Moreover, there is evidence that ambient concentrations of particulate matter can exacerbate viral infections (Ciencewicki and Jaspers, 2007; Croft et al., 2018, 2020) which may have further relevance in the context of the COVID-19 pandemic and potential future challenges of a similar nature.

Most EU Member States report $PM_{2.5}$ observations below the European Air Quality Directive annual limit value of 25 $\mu g/m^3$ (AQD, 2008), but 70% of the AQ stations in Europe report annual observations above the World Health Organization (WHO) 2005 annual guideline of 10 $\mu g/m^3$ (EEA, 2019). This WHO guideline has very recently been updated and is now set to 5 $\mu g/m^3$ (World Health Organization, 2021). This guideline is based on evidence with high or moderate certainty of an

---

[1] $NO_X = NO_2 + NO$.

[2] p.m.$_{2.5}$ – Particulate matter with a diameter of 2.5 μm or less; PM_{10} - Particulate matter with a diameter of 10 μm or less; VOC = Volatile Organic Carbons; SO2 – Sulphur dioxide.

[3] There is a minor efficiency penalty when ASHP's are operating in negative Celsius ambient temperatures. However, auxiliary heating can be used to supplement room temperatures as necessary. In general, given that homes which install heat pumps must have a low heat loss indicator, we assume that the types of auxiliary heating are more likely to be on demand electrical heating systems, which are compatible with an airtight home.

[4] CO – Carbon monoxide; BC – Black carbon.

[5] SO_X – Sulphur oxides.

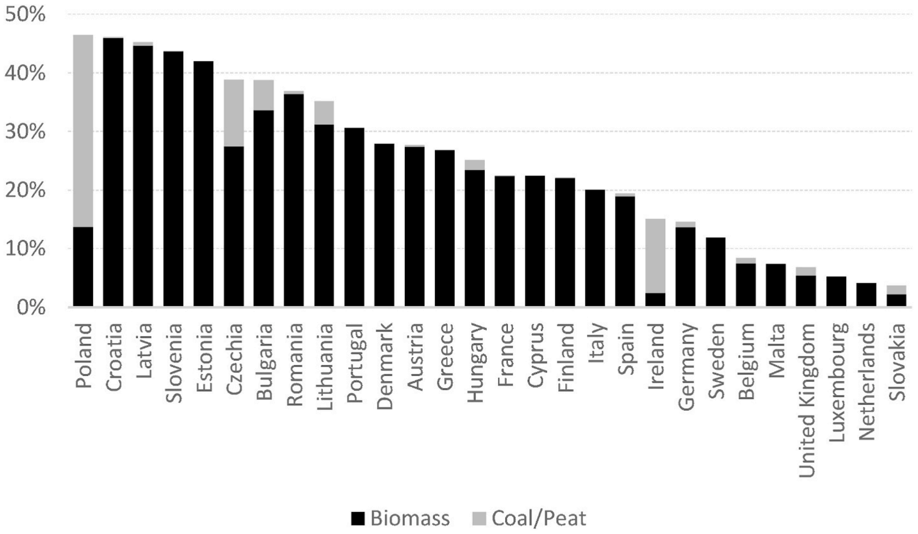


Fig. 1. Individual country solid fuel use in the residential sector in the EU in 2018. Data for chart from (Enerdata, 2021).

association between the pollutant and a specific health outcome. Recent exposure-response studies have been conducted at very low particulate concentrations and have found no evidence of a cut-off point of 'no effect' on health. For example, in the framework of the ELAPSE[6] project, Brunekreef et al. (2021) concluded that "the shape of the associations with natural-cause mortality showed steeper slopes at lower exposures, with no evidence of concentrations below which no associations were found for $PM_{2.5}$, BC, and NO_2." Moreover, long-term exposure to levels of air pollution below the EU limits are associated with the development of chronic obstructive pulmonary disease (Liu et al., 2021a), asthma (Liu et al., 2021b), and lung cancer (Hvidtfeldt et al., 2021b) and this is all possible below the 2005 WHO guidelines. Moreover, regarding $PM_{2.5}$ and its composition, research concluded that $PM_{2.5}$ originating from oil combustion, biomass burning, and secondary inorganic aerosol formation is connected to an increased risk of lung cancer (Hvidtfeldt et al., 2021a). Even in the Nordic countries, which report comparatively low annual mean concentrations that are usually below the European Air Quality Directive annual limit (and below 2005 WHO guidelines), ambient air pollution is still identified as one of the main public health risk factors (Lehtomäki et al., 2018). The economic costs of air pollution-related deaths in Denmark, Sweden, Finland, and Norway in 2015 were estimated to be €7 billion (Im et al., 2019).

Ireland, like the Nordic countries, does have comparatively low $PM_{2.5}$ concentration levels (EPA, 2020). The $PM_{2.5}$ measurements in the Air Quality monitoring network have generally stayed below the EU annual limit value of 25 $\mu g/m^3$ and, by 2017, Ireland had achieved the national exposure reduction target of a 10% decrease of the 3-year mean in background stations between 2011 and 2020 (EPA, 2018a). However, in the estimate of premature deaths attributable to $PM_{2.5}$ referenced above (EPA, 2019), the specific estimate for Ireland of 1100 premature deaths in 2016 remains a concern. The Irish Environmental Protection Agency (EPA) in their annual Air Quality Assessment reports (EPA, 2020) have used their monitoring network data to establish a clear connection between high concentrations of $PM_{2.5}$ and solid fuel burning for home heating. In 2019 the EPA Ambient Air Quality Monitoring (AAMP) network of monitoring stations has been expanded by 24 to comprise 84 stations nationwide, and of these 30 stations monitored $PM_{2.5}$ in 2019. Measurements across these stations in 2019 show that the relatively high annual limit value was never breached, although 5 of the 30 stations had values above the prior WHO annual AQG (annual guideline of 10 $\mu g/m^3$). The WHO daily guide value (25 $\mu g/m^3$) was breached on a number days at most of the stations (EPA, 2020).[7]

Fig. 2 presents the *chemistry transport model* (CTM) EMEP (Simpson et al., 2012) surface air concentrations of the gridded-average $PM_{2.5}$ annual mean concentrations for the year 2015 in Ireland. The maximum

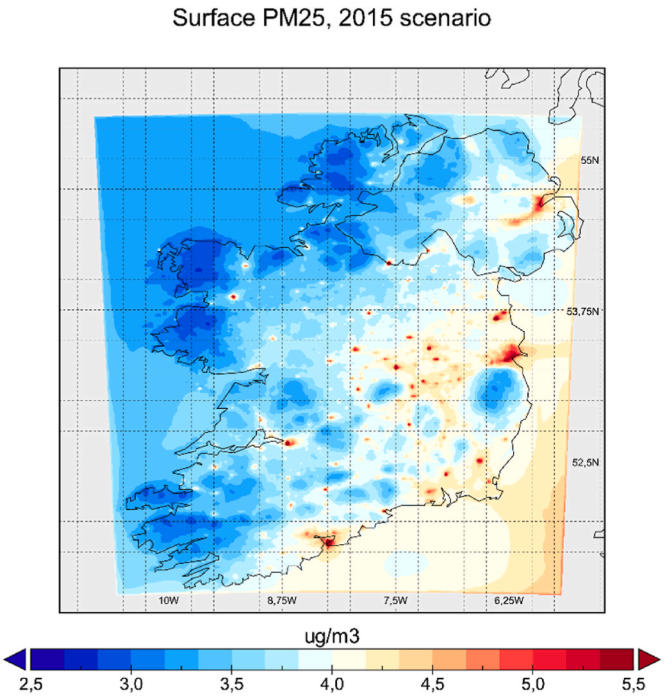


Fig. 2. Modelled surface $PM_{2.5}$ annual mean concentrations ($\mu g/m^3$) for the calendar year 2015 (Ó Broin et al., 2019). Map created with EMEP model simulation.

---

[6] ELAPSE stands for Effects of Low-Level Air Pollution: A Study in Europe.

[7] We note that Indoor air quality is also relevant to health impacts of air pollution, and indoor air pollution is associated with both the levels of outdoor ambient air quality, and the indoor heating and cooking sources (Salthammer et al., 2014; Vilčeková and Nejadkoorki, 2011). However, data are unavailable in the context of this current study which deals with outdoor ambient air quality only.

grid value is 10 μg/m^3 and the national mean is 4 μg/m^3. The contribution of secondary organic production of $PM_{2.5}$ is negligible in the model as compared to direct-emission sources; thus, the highest concentrations (orange and red colour) are found near the main sources of the direct emissions of pollutants, i.e., roads, residential areas, and industrial facilities. The elevated $PM_{2.5}$ annual mean concentrations are generally found in areas of significant population density.

Fig. 3 shows the $PM_{2.5}$ surface annual concentrations derived from residential heating emissions i.e., the difference with Fig. 2 is that all non-residential sector emission sources have been removed. We can observe agglomerations with contributions of 1.5–2 μg/m^3 to the total $PM_{2.5}$ concentration. Interestingly it is not the cities e.g., Dublin and Cork that stand out in Fig. 3, rather it is mostly a grouping of midland towns, which have we have encircled in green.[8] Within the green circle are the towns in Co. Westmeath (Athlone), Co. Longford (Longford Town), Co. Offaly (Tullamore) and Co. Laois (Portlaoise) as well as other towns that have populations greater than 5000. The latter includes Mullingar in Co. Westmeath, Edenderry, and Birr in Co. Offaly, Portarlington and Mountmellick in Co. Laois, Ballinasloe in Co. Galway, and Roscrea in Co. Tipperary. Examining Fig. 2 it can be observed that these towns are also relative ambient air pollution hotspots within the broader Irish context.

The transition away from solid fuels in the residential sector is of clear relevance to air quality and human health, and there are many factors to consider which influence residential home heating fuel choices (Fu et al., 2014). Much of the anticipated change in residential heating is now being driven by climate policy, and this is clearly in evidence in our case country – Ireland. The national climate action plan (DECC, 2021) sets an ambition to electrify residential heating systems in some 600,000 homes across Ireland by 2030, relying predominantly on ASHP technology. The current national policy goal in the climate action plan includes 400,000 ASHP retrofits into existing homes, with an initial focus on oil-fired heating systems. These are recognised as an ideal target for the retrofits due to the potential energy cost savings, space to accommodate the required technology (in place of an oil tank), and other factors (Kelly et al., 2016).

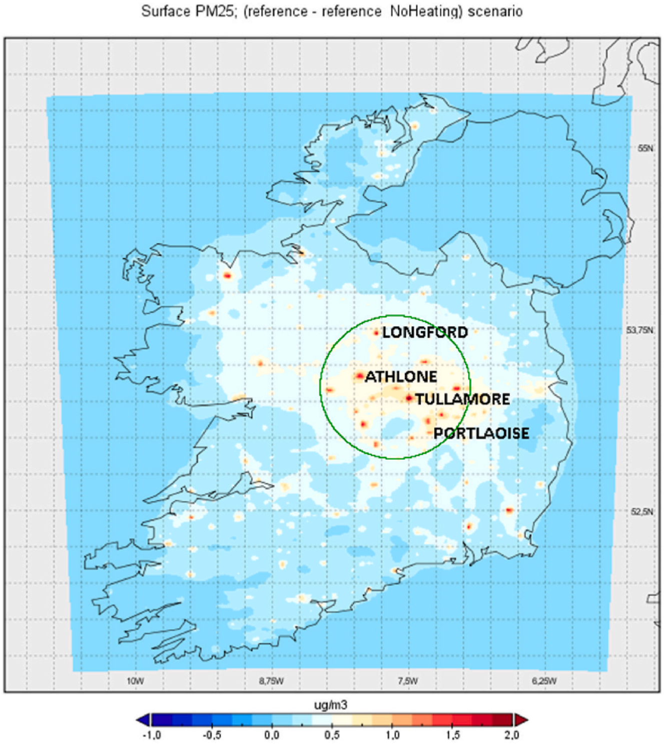


Fig. 3. Modelled Residential sector surface $PM_{2.5}$ annual mean concentrations in 2015. Map created by subtracting concentrations resulting from stationary combustion in industry and public power from the total shown in at Fig. 2. Green circle delineates area with higher incidence of 'hot-spot' $PM_{2.5}$ concentration towns, including county towns of Co. Longford, Co. Westmeath, Co. Offaly, and Co. Laois.

Census data shows that oil fired heating systems account for approximately 40% of the residential heating market in Ireland and primary solid fuel heating accounts for 12% (SEAI, 2018). The Irish government's retrofitting policies are highly ambitious and labour intensive, and thus can only happen on a phased basis given the scale of action and the costs (state, private and transactions) involved. This paper analyses the potential for prioritising certain ASHP retrofits based on a targeted approach such that comparable climate outcomes are achieved, whilst additional air pollutant emission reductions and lower ambient air pollution concentrations are delivered. The objective is to identify specific air-pollution 'hotspot' communities to enable spatial targeting of heat pump retrofits that can deliver on climate ambitions, whilst also delivering annual average ambient air-quality improvements and greater support to a just climate transition. The approach and findings will be of relevance to a broader international policy audience as they invest to deliver on their own stronger climate action strategies in the coming years.

3. Methodology

This paper simulates air pollutant and greenhouse gas emission outcomes from the Irish residential sector by 2030 in two alternative scenarios for the deployment of the 400,000 ASHPs that are planned to replace existing fossil fuel-based heating technologies across Ireland. The objective difference between the scenarios is that in the second scenario the deployment of the ASHPs is designed to target ambient air-quality hotspots, in order to address multiple policy goals simultaneously. Specifically, that scenario is analysing and quantifying how a partially targeted approach to the ASHP retrofit deployment, can offer greater reductions in national air-pollutant emissions, an improvement in ambient air quality, further support for a just transition and improved health outcomes for citizens in the identified residential air pollution hotspots.

3.1. Scenario 1

In the first scenario, the 400,000 ASHPs are deployed throughout the country to replace 80% oil, 10% gas, 5% solid fuel, and 5% electric heating systems. This corresponds to replacing 320,000 oil boilers, 40,000 natural gas and 20,000 each of solid-fuel and electric systems. The 80% proportion of oil boilers is chosen because the dominant residential heating types in Ireland are either oil or gas systems, representing almost ¾ of the household heating systems as of the 2016 census (SEAI, 2018). As the policy explicitly prioritises installing ASHPs in place of oil fired systems, and as research has indicated a far stronger economic case for oil households to install an ASHP relative to a household using gas (Kelly et al., 2016), we elect to assign the majority of the ASHP retrofits against oil fired systems. Table 1 presents census data for the residential heating-energy carrier numbers in Ireland in 2016. It is assumed that the ASHPs are deployed in a range of dwellings, e.g., detached, semi-detached and bungalows. The small proportion of electric and solid fuel boilers is to reflect the smaller share of these two energy carriers in the housing stock, e.g., <150,000 electric heating systems in 2016 (Table 1).

The Sustainable Energy Authority of Ireland (SEAI) have two criteria

---

[8] The green circle in Fig. 3 has a diameter of approximately 100 KM meaning that it covers an area of 7850 KM^2 and stretches East West from Edenderry to Ballinasloe and North to South from Longford to Roscrea.

Table 1
Census data on number of home heating boilers in Ireland in 2016 (SEAI, 2018).

All Dwellings	**1,697,665**
No central heating	23,174
Oil	686,004
Natural Gas	569,166
Electricity	146,302
Coal	86,611
Peat	90,029
Liquid Petroleum Gas	9990
Wood (incl. pellets)	33,976
Other fuels	11,068
Not stated	41,345

for a grant subsidy to install an ASHP which are relevant to expected ASHP deployment and uptake rates in the market. Specifically that the dwelling has been built before 2011 and that it has low heat loss (SEAI, 2020a). Although not exact, we use a proxy for low heat loss, and assume that low heat loss is the case where the dwelling has an Irish Building Energy Rating (BER) of B2[9] or better. Thus, when replacing the defined numbers of boilers with ASHPs for each energy carrier in the scenario, we start with the dwellings built before 2011 that have the highest level of energy efficiency i.e., a BER of A. A record is made of the number of dwellings for each BER category in which an ASHP is then deployed (See Table 6). However, in this scenario there is no spatial targeting for the deployment of heat pumps, rather our approach parses a database of Irish dwellings looking for 320,000 dwellings with oil boilers, 40,000 dwellings with natural gas boilers and 20,000 dwellings each with solid-fuel boilers and electric storage heating systems whose BER's are closest to B2. The resultant spatial distribution of heat pumps in Scenario 1 is thus dependant on where the most efficient dwellings are currently located rather than any other geographic factor. For those deployed in dwellings with a BER of less than B2, the extra retrofit investment needed to make them '*ASHP-ready*' is also estimated (see Section 5.1). The calculated outcome from Scenario 1 is the reduction in greenhouse gas emissions and air-pollutant emissions from the replacement of all four categories of boilers with ASHPs. It should be noted that this approach of targeting homes with higher BERs and oil systems will deliver more conservative outcomes in terms of emission reductions as well as lower costs per house, than a strategy which targeted the worst performing homes, which would require substantial fabric retrofit costs to prepare for heat pump technology, but which would offer greater emissions abatement potential (see Table 5).

3.2. Scenario 2

In the second scenario the deployment of a proportion of the ASHPs is targeted to areas of the country with higher-than-average annual average concentrations of $PM_{2.5}$. Figs. 2 and 3 are used to identify these areas of the country where the ASHP deployment in Scenario 2 could target relative air pollution hotspots. On review of the sectoral spatial emissions inventory data, it is clear that the higher concentrations of $PM_{2.5}$ in these towns are primarily due to the use of solid fuels for primary and secondary heating. Thus, the maps have somewhat revealed the means to target ASHP deployment to address ambient air pollution hotspots. For County Offaly, for example, Tullamore, Birr, Banagher and Edenderry are identified, and for County Westmeath, Athlone and Mullingar are shown. An inventory of the boilers in all of the Midland towns circled in Fig. 3 has been created using data from Kelly et al. (2016). It shows that there are 2411 coal boilers, 7518 peat boilers, and 789 wood boilers i.e., 10,718 solid-fuel boilers across all of these towns[10]. In the targeted scenario 2, all of these 10,718 boilers are replaced with ASHPs. This results in just 9282 (20,000–10,718) solid-fuel boilers which are then replaced across the rest of the country (without targeting) and the same 320,000 oil, 40,000 natural gas, and 20,000 electric boilers. Thus, in both Scenario 1 and Scenario 2 the same proportions of oil, natural gas, solid fuel, and electric heating systems are replaced. The difference is simply the refined targeting of 10,718 specific solid fuel boilers.

For both scenarios, we require estimations of the total annual emissions of CO_2, CO, NH_3, NO_X, $PM_{2.5}$, PMcoarse, SO_X, and VOC. CO_2 emissions are relevant for climate policy implications (i.e., the level of sectoral CO_2 emissions). The other emissions are needed as inputs for the CTM model in order to estimate the impact on $PM_{2.5}$ air concentrations of the two scenarios relative to the reference simulation for 2015. Emissions of residential sector CO_2, $PM_{2.5}$ and SO_X are estimated in this work using the model described in Section 3.3 and Section 3.4, while the emissions of other pollutants and sectoral emissions are taken from the official emissions as reported to the UN through the Convention on Long-Range Transboundary Air Pollution (LRTAP) for 2015. The change in CO_2 emissions in the residential sector occurs from the oil, natural gas, coal, and peat boilers, which are replaced with ASHPs, while the change in $PM_{2.5}$ and SO_X occurs from the solid fuel (coal, peat, and wood) boilers which are replaced with ASHPs. SO_X emissions from oil and natural gas boilers are negligible, while CO_2 emissions from burning wood are ignored due to wood being classed as a renewable.

A modelling construct of the work is that the BER of each individual dwelling is not known. Instead, the average BER for each Small Area (SAs)[11] has been calculated in a previous exercise (Kelly et al., 2016) and used. Thus, when choosing dwellings in which to deploy an ASHP, we can list the SAs where the average BER is B2 (or rather, relatively higher) and then remove the dwellings built after 2011. This means that there may be a slight difference in estimated $PM_{2.5}$ and SO_X emissions in Scenario 1 and Scenario 2 as the average BER of the small areas which are $PM_{2.5}$ hotspots may be lower than some of the small areas in which solid fuel boilers are otherwise replaced with ASHPs in Scenario 1. In modelling terms both scenarios are simulations and without a time dimension.

It is also assumed that dwellings suitable for an ASHP, i.e., with a BER of at least B2, would no longer use emission generating secondary heating. This is an important assumption as according to earlier research, secondary heating for fireplaces and stoves can represent approximately 50% of residential coal and peat consumption (SEAI, 2013). It is also assumed that no new modern or non-wood stoves are installed in the 400,000 dwellings where ASHPs are installed. Whilst important, these assumptions are credible as a non-emitting auxiliary heating system (e.g., on demand electric heater) would be far more compatible with the type of airtight home required for an ASHP installation in Ireland. The air-pollutant emission outcomes are simulated first, and then used to model their contribution to $PM_{2.5}$ ambient air-pollutant concentrations.

---

[9] A Building Energy Rating (BER) certificate indicates a dwelling's energy performance and is similar to the energy label for household appliances. The system in Ireland has been created by the SEAI and a certificate rates the energy performance of a home on a sliding scale of A-G with an A rated house being the most energy efficient. An A rated house has a unit consumption of 25 KWh/m^2/year while a G-rated has 450 KWh/m^2/year. A B2 BER correspond to a unit consumption of 100 KWh/m^2/year.

[10] There are also 501 dwellings in these towns where there are no central heating systems at all. It can be assumed that they are using solid fuel heating via fireplaces and stoves. These dwellings have not however been targeted in this work.

[11] Small Area level is used in the national census data to cluster groupings of households mostly in the range of 80–120 homes. In total there are 18,641 SAs in Ireland.

3.3. Emissions model

An Irish instance of the IIASA GAINS Integrated Assessment Model (Amann et al., 2011; Kelly et al., 2017) is applied to calculate emissions of each greenhouse gas and air pollutant species examined based on the following formula:

$$\Sigma E_{ijk} = A_{ijk} D_{ijk} I_{ijk} F_{ijk} \tag{1}$$

where E = emissions, A = activity, D = duration of use, I = energy intensity, F = emission factor, i = sector, j = sector specific technology and k = air pollutant species. For example, for the residential sector E = emissions, A = number of boilers (see Table 1), I = energy intensity of boiler, F = emission factor, j = energy carrier and k = air pollutant species.

The average energy intensity per boiler in the residential sector is estimated as final energy consumption for an energy carrier divided by the number of boilers using that energy carrier. Emission factors for CO_2 are listed in Table 2 while data on emission factors for $PM_{2.5}$ and SO_X are Tier 1 Emission Factors (EPA, 2018b). Those for $PM_{2.5}$ are listed in Table 3. The tables of Tier 1 Solid Fuel combustion Emission Factors are from the EMEP/EEA air pollutant emission inventory guidebook – 2016, a guidebook which supports the reporting of emissions data under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) and the EU National Emission Ceilings Directive. On the matter of condensables, the guidebook states that the TSP, PM_{10} and $PM_{2.5}$ emission factors have been reviewed and that it is unclear whether they represent filterable PM or total PM (filterable and condensable) emissions. Thus, a definitive statement on the inclusion or exclusion of condensables cannot be provided for these emission factors. However, whilst this introduces some ambiguity with respect to the condensables question, the method and emissions remain consistent with current international reporting. Furthermore, given the focus on the relative impact of the policy scenarios, the policy findings are not adversely affected.

3.4. Air quality modelling

All the air quality modelling in this study was conducted with the chemistry-transport model EMEP (Simpson et al., 2012)[12].

The EMEP model includes both primary and secondary aerosol species (and considers both inorganic and organic fractions). The gas/aerosol partitioning between gas and fine-mode aerosol phase in the system of SO4–HNO3–NO3–NH3–NH4 uses the MARS equilibrium module of Binkowski and Shankar (1995). The secondary organic aerosol modelling uses the so-called volatility basis set (VBS) approach (Robinson et al., 2007; Donahue et al., 2009). $PM_{2.5}$ represents the model size mode of the particulate matter with aerodynamic diameter up to 2.5 μm and is calculated as follows[13]:

$$PM_{2.5} = SO_4^{2-} + NO_3^- (fine) + NH_4^+ + SS\ (fine) + MD\ (fine) + SOA\ (fine) + PPM_{2.5} + 0.27 \times NO_3^- (coarse) + water$$

Table 2

CO_2 emission factors for fossil fuels (SEAI, 2016).

Carbon Intensity Gas	**kg/MWh**	**202**
Carbon Intensity Oil	kg/MWh	274
Carbon Intensity Coal	kg/MWh	342
Carbon Intensity Peat Briquette	kg/MWh	355.9

Table 3

$PM_{2.5}$ emission factors for fossil fuels (EPA, 2018b).

Tier 1 p.m.$_{2.5}$ Emission Factors		
Coal/Peat	kg/GWh	1106
Gas	kg/GWh	3.33
Oil	kg/GWh	5.28
Biomass	kg/GWh	2056

Two domains were simulated: Europe (horizontal resolution of 50 km × 50 km) and Ireland (horizontal resolution of 2 km × 2 km). The simulation for Europe produced the boundary conditions for all of the simulations in the Ireland domain. The boundary conditions for the European-wide simulation are climatological fields based on

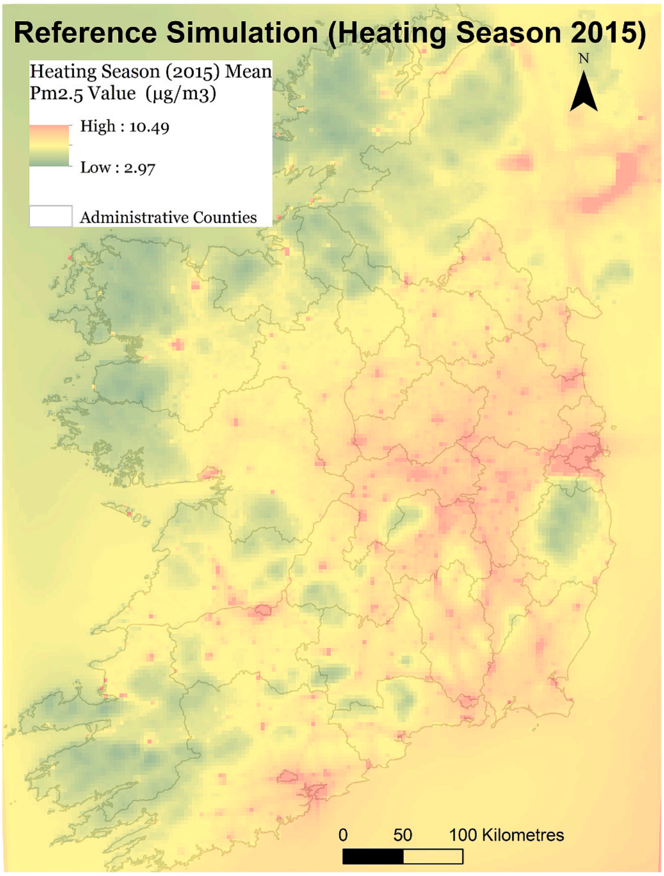


Fig. 4. Modelled surface $PM_{2.5}$ mean concentrations (ug/m3) for the months October to March in 2015.

---

[12] Version EMEP_OpenSource.rv4.17.

[13] SO_4^{2-} - Sulphate; NO_3^- - Nitrate; NH_4^+- Ammonium; SS - Sea Salt; MD - Mineral Dust; SOA – Secondary Organic Aerosol; PPM – primary particulate matter originating directly from anthropogenic emissions; water – particle-bound water.

observations. The emissions for the European domain are from the EMEP standard inventory, in which anthropogenic emissions are based on reported country yearly total emissions in 2015, redistributed to a 50 × 50 km^2 polar stereographic EMEP grid. The country total emissions were provided for 10 anthropogenic source-sectors. To produce the meteorological data for both Europe and Ireland domains we used the Weather Research and Forecast Model (WRF) version 3.9.1 with NCEP FNL input data in a nested system. As the work presented in this paper focuses on residential sector heating systems, we present results for the heating season part of the year which is October to March. Fig. 4 shows model results of concentrations of $PM_{2.5}$ across the island of Ireland for the heating season in 2015. This is the reference against which the two scenario results are measured.

3.4.1. *Emissions for air quality modelling*

As stated previously the main data source for the air pollutant concentration modelling was the official emissions as reported to the UN under the Convention on Long-Range Transboundary Air Pollution (LRTAP) for 2015. These emissions have been spatially distributed in the MapEire project, on a 1 km grid. The spatial distribution was conducted individually for each sector by the University of Aarhus SPREAD model, which uses proxy data to determine the activity of each sector in each grid. Typical activity data is population density, land use, roads and railways and the industry grid (Nielsen and Plejdrup, 2016). Exceptions were the sectors of shipping, residential heating, and traffic. The source for the shipping emissions was the data inventory of the Finnish Meteorological Institute (FMI) for 2015 with a 0.1° resolution (Johansson et al., 2017). This inventory is based on individual ship position, speed and direction recorded every 6 min through the ship-AIS system by all commercial vessels. This information is coupled with IMO registry ship engine information to produce emissions. The emissions for the transport sector are spatially distributed across the country at road network level based on annual average daily traffic values (AADTs) and commonly available information from existing geographical data, census data, traffic data and vehicle fleet data (Fu et al., 2017). For the reference year and both scenarios, estimated residential sector emissions of $PM_{2.5}$ and SO_X are distributed at Small Area Level based on both primary and secondary fuel use patterns across Ireland, which are calculated using census data and CSO Household Budget survey data by EnvEcon (Kelly et al., 2020; Ó Broin et al., 2019). For Northern Ireland (UK), the TNO-MACC (Kuenen et al., 2011) was used. These data have a spatial resolution of approximately 7 × 7 km^2, rescaled to match the official EMEP country total emissions. For scenarios 1 and 2, residential emissions for $PM_{2.5}$ and SO_X were recalculated using the same methodology as above.

3.4.2. *Evaluation of air quality modelling for the reference simulation*

The EMEP-WRF modelling results from the inner grid (2 km resolution) were compared to measurement data of $PM_{2.5}$ at six monitoring stations of the Irish Environmental Protection Agency. These data can now be accessed at a new EPA resource - https://airquality.ie/The sites include one background rural station (“Mayo Claremorris”, located a few kilometres south of Claremorris in the county of Mayo) and five suburban background sites, two in Dublin, one in Cork, one in Ennis (“Clare Ennis”), and one in Bray (“Wicklow Bray”) some kilometres south of Dublin.

Fig. 5 presents the daily measured and modelled concentrations during the heating season in 2015 (Jan–Mar and Oct–Dec) in μg m^{-3}. Except for Clare Ennis the timeseries show a fairly good agreement during these six months, with the occurrence of most episodes reproduced very well by the model. Although a general underestimation of the levels is seen, an underestimation of the highest peak episodes is a common feature by atmospheric grid models and reflects the inherent limitations given by the grid averaging. Although the WRF/EMEP model is zoomed down to a fine scale, a grid square average concentration of 2 km × 2 km will not be able to reproduce the highest peak levels observed at a monitoring station. Furthermore, comparisons with observational data always raise the question of representativity. Particularly in urban and suburban areas, where large spatial gradients in the concentration fields will make it harder to find sites that are representative of a larger domain.

The results from Clare Ennis show a significantly poorer agreement between modelled and observed concentrations both with respect to the absolute levels and the timeseries development. The measured $PM_{2.5}$ level at that site is substantially higher than modelled.

Fig. 6 presents five statistical metrics for each of the six stations as calculated by the R function ‘ModStats’ in the openair package (Carslaw and Ropkins, 2012). These are normalized mean gross error (NMGE), linear correlation coefficient (r), fraction of predictions within a factor or two (FAC2), mean bias (MB) and root mean square error (RMSE). The reader is referred to the openair manual as given in the references for the definition of these statistical metrics. The statistical computation was done only for the data from the six-months heating season (Jan–Mar + Oct–Dec). Note that NMGE, r, and FAC2 are dimensionless statistics whereas MB and RMSE are given in μg m-3.

As discussed with respect to the timeseries, the statistical evaluation shown in Fig. 6 confirms a particularly poor performance at Clare Ennis as compared to the other five stations. This is seen for all five metrics, i.e., low correlation coefficient, high bias etc. The results for the other stations are quite even as seen by the correlation coefficient and the mean bias for example. A correlation coefficient of around 0.6 is found for all sites and a mean bias in the range −3 to −6 μg/m^3. This confirms that the model underestimates $PM_{2.5}$ levels at all sites. FAC2 is in the range 0.5–0.65 (except for Clare Ennis) implying that 50–65% of the modelled values lie within a factor of two of the observed values.

3.4.3. *EMEP simulations*

Table 4 lists the five EMEP simulations that are presented in this paper.

4. Results

This section presents the modelling results for greenhouse gas emissions (CO_2), air pollutant emissions ($PM_{2.5}$) and air pollutant concentrations for the reference case and the two scenarios where different strategies for the deployment of the 400,000 ASHP retrofits are applied as described in Section 3.

4.1. *Greenhouse gas emissions*

Figs. 7 and 8 present reference (2015) final energy demand in the Irish Residential Sector and the corresponding estimates of CO_2 emissions. The two 400,000 ASHP scenarios are also included in those Figures and indicate that, compared to the reference, the policy could deliver an approximate 18% reduction in final energy demand and a 28% reduction in CO_2 emissions for the residential sector in both cases.

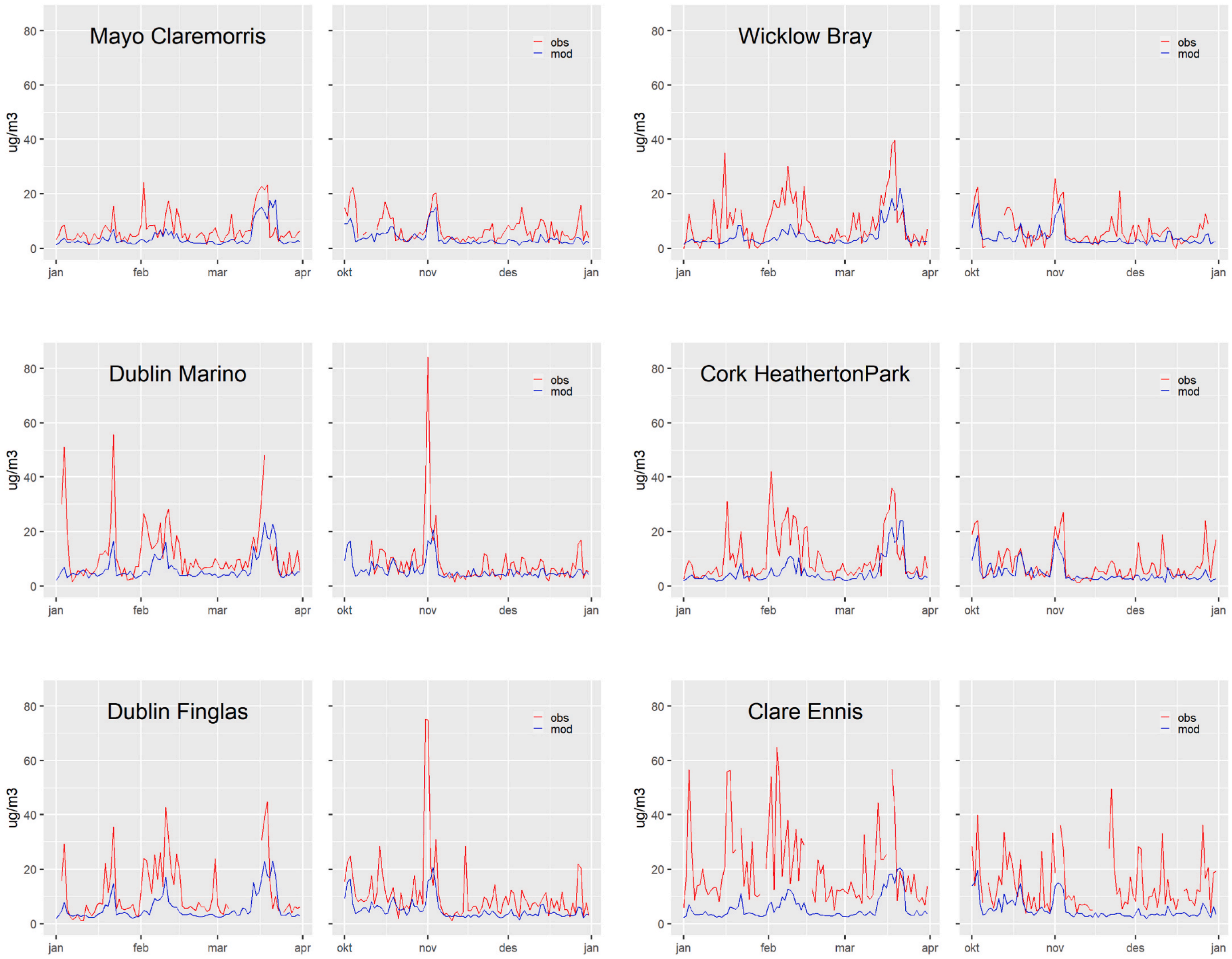


Fig. 5. Measured (red) and modelled (blue) daily PM2.5 values at six Irish stations during Jan–March (left panels) and Oct–Dec (right panels) in 2015. The data are given in µg m-3.

As the deployment of 400,000 ASHPs is but one of a suite of measures that will support efforts to decarbonize the Irish residential sector, a 28% reduction in total emissions from this action in the sector is significant. A closer examination of the individual energy carriers reveals that the results in both scenarios are identical for oil, electricity, and gas, and that there are only slight differences observed for coal, peat, and renewables. These latter differences are as a result of targeting approximately 11,000 ASHPs at specific air-pollutant hot-spot towns in the Midlands. There is, of course, also an increase in final electricity demand in both scenarios as a result of the increased electricity use for the ASHPs.[14] However, as indicated, in this paper we are not investigating the merits of the established Government ambition to retrofit 400,000 ASHPs, rather we are investigating the potential for positive synergistic outcomes where the national ambition is refined with an element of targeting. The results confirm that the targeted strategy would, as expected, in no notable way compromise the greenhouse gas abatement potential of the 400,000 ASHPs policy without a targeted approach. Thus, our focus shifts to exploring the scale of the potential synergies with regard to emissions of air-pollutants and improvements in ambient air-quality that may be realised with the targeted policy.

4.2. *Air pollutant emissions*

Fig. 9 presents $PM_{2.5}$ emissions for the reference and the two ASHP scenarios. $PM_{2.5}$ is reduced by 10% and 12%, respectively, for both scenarios. The reductions in both scenarios are of course similar as 11,000 out of 400,000 boilers does not have a large absolute effect. The slightly different shares we observe reflect the spatial selection factors influence on outcomes as described earlier in Section 3.2.

4.3. *Air pollutant concentrations*

Fig. 10 shows the impacts of the two residential heating emission scenarios on surface air concentrations of $PM_{2.5}$ (Fig. 10a for Scenario 1 and Fig. 10b for Scenario 2). The values shown are changes in the mean

---

[14] A contemporary overview of the prospects for the decarbonisation of the Irish Power System including a discussion on pathways to a 100% renewable energy system in Ireland by 2050 is provided by Yue et al. (2020). Their work also includes a comprehensive literature review that extends well beyond the scope of this paper, but which touches on relevant technical and policy issues for this context. These include meeting peak demand with battery storage; management of low-demand periods; high investment costs in flexibilities and new capacities; extreme weather conditions; access to renewable data; constraints on geographical allocation of storage technology; government regulations; storage and interconnectors.

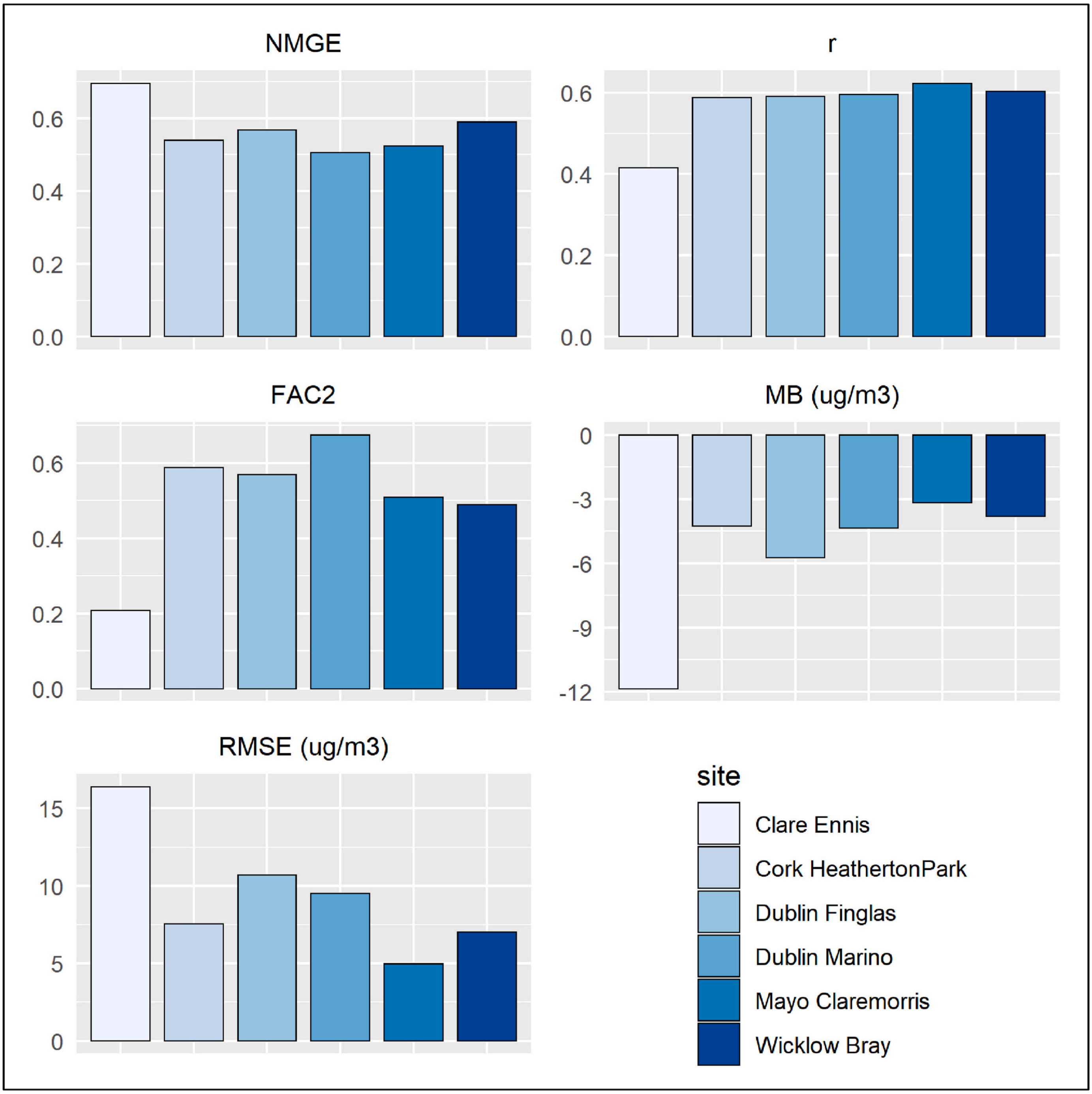


Fig. 6. Statistical performance metrics for the modelled vs observed PM2.5 concentrations at six Irish monitoring stations. Daily mean levels during the heating season (Jan–Mar + Oct–Dec) in 2015 were used when calculating these statistics. The statistics are: NMGE = Normalized mean gross error, r = linear correlation coefficient, FAC2 = Fraction of predictions within a factor or two, MB = Mean Bias, RMSE = Root Mean Square Error.

concentrations for the heating season, that is, October to March. On Fig. 10a, we can see that the maximum decrease we achieve in Scenario 1 is 1 μg/m3 in the top Northwest of Ireland in the town of Buncrana. In the Midlands area, Scenario 1 has its highest decrease as just 0.47 μg/m^3 (Longford and East of Edenderry). However, when we apply the spatially targeted emission reduction strategy of Scenario 2 (Fig. 10b), where the policy is focused on solid fuel use in specific Midland towns that represent relative ambient air pollution hotspots, we observe far more substantial decreases in the range of 1–2.3 μg/m^3, i.e., 20–34% reductions relative to the reference simulation.

5. Implications for policy design

When considering the targeted approach to the deployment of ASHP's proposed in this work, the practicalities of the implementation of the scenarios should be considered. The results shown in Fig. 10 are for a simulation without a time dimension. The Irish government target is to deploy 400,000 heat pump retrofits by 2030, and so an initial question arises as to whether it reasonable to assume that this can happen in a country of Ireland's population size (approximately 5 million as of 2021) over a ten-year period. Sovacool and Martiskainen (2020), write that fast transitions of European heating systems can take

Table 4
Simulations using EMEP presented in this study.

Simulation	Description	Figure
Reference	EMEP simulation for the calendar year 2015 as described in the text.	Fig. 2
	Changes relative to Reference	
Ref_noSector2	Emissions from Residential sector for the heating season only i.e., no emissions from other stationary combustion sources included e.g., Industry and Power generation.	Fig. 3
Scenario 1	Heating season residential sector emissions reduced by replacement of 400,000 boilers using oil, natural gas, solid fuels, or storage heating with ASHP's.	Fig. 10a
Scenario 2	Heating season residential sector emissions reduced by *targeted* replacement of 400,000 boilers using oil, natural gas, solid fuels, or storage heating with ASHP's.	Fig. 10b
With_Measures	Emissions in 2030 from a scenario developed by the Irish EPA considering no additional policies and measures beyond those already in place in 2018 and including 175,000 ASHP's being installed.	Fig. 12

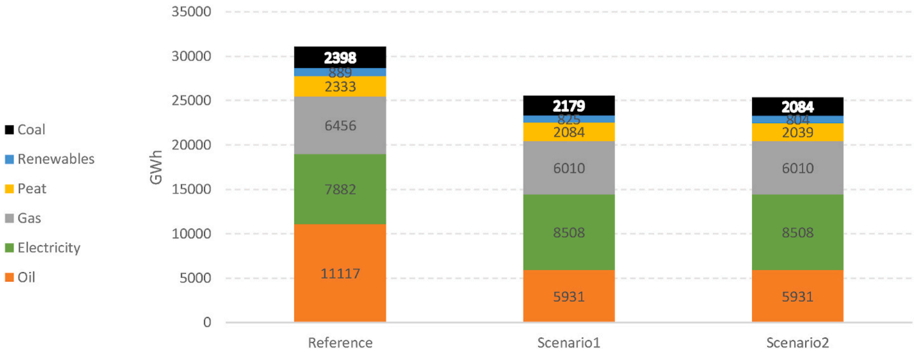


Fig. 7. Final energy demand in the Residential Sector by energy carrier in the reference in 2015 (measured (EPA, 2018c)) and in Scenario1 and Scenario2 (estimated).

Fig. 8. CO_2 emissions from the Residential Sector by energy carrier in the reference in 2015 (measured (EPA, 2018c)) and in Scenario1 and Scenario2 (estimated in this work).

from decades to a half a century, although Finland has managed to move from having almost no ASHPs installed in the year 2000 to over 900,000 in 2018. Thus, 400,000 in a decade to 2030 may be deemed plausible, albeit exceptionally challenging with no time to waste.

In this section we further discuss various aspects of the scenarios in terms of costs and supports, their role in alleviating energy poverty risk, and the contribution to emission reduction targets.

5.1. *Cost and supports*

The estimated up-front costs presented in this section include an approximate cost of installation for an ASHP and, where necessary, an indicative cost of retrofitting dwellings to make them ASHP ready. At the time of writing there are less than 400,000 dwellings in the Republic of Ireland that have a BER of B2 or greater. Thus, even if only Scenario 1 is implemented, as per the Government Climate Action Plan, retrofitting costs will certainly accrue to make sufficient dwellings ready for an ASHP retrofit.[15]

The cost of installation of an ASHP in an Irish home has been estimated to be between €8500 and €14,500 (Electric Ireland, 2020), with the cost varying considerably with the size of the pump and the complexity of the install.[16] Assuming an average cost of €11,000 for the installation of an ASHP in a dwelling, gives an up-front cost for the installation of 400,000 ASHPs of €4.4 billion. These ASHP install costs for the 400,000 dwellings must then be added to the costs of making sufficient homes ASHP-ready as necessary. In this regard we use the BER B2 rating as a proxy for a home being ASHP-ready.

Table 6 shows the numbers of homes retrofitted in this work per scenario and energy carrier to ensure an adequate number are ASHP-ready. The total number of homes to be retrofitted in this context is 388,384. Table 6 shows that most ASHP's will go to oil heated dwellings with a current BER of D1. It is also shown in Table 6 that in Scenario 2 the solid fuel heated homes with current BER's of as low as G will have ASHP's deployed in them, which suggests substantial retrofitting costs

---

[15] Here we are distinguishing again between the 200,000 heat pumps that are to be installed in new buildings as part of new building regulations, and the 400,000 that are to be retrofitted into the residential sector.

[16] One consultant estimates the all in cost of the installation of a heat pump, i.e. including materials, labour new efficiency radiators and hot water cylinder this might cost in the region of €12,500 to €15,000 (Irish Times, 2020).

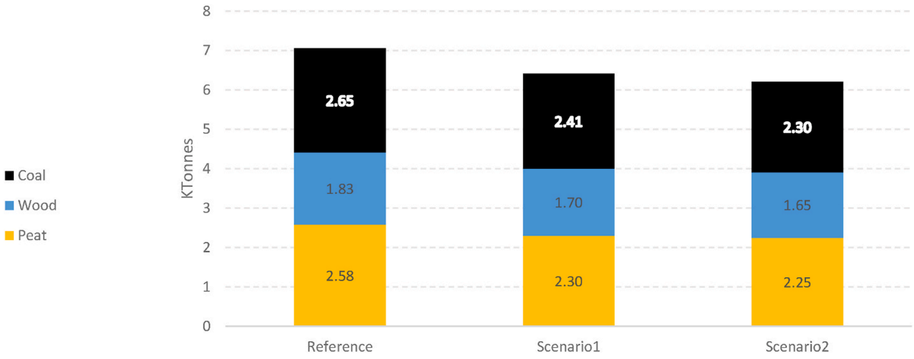


Fig. 9. $PM_{2.5}$ emissions in the Residential Sector by energy carrier in 2015 in the Reference (measured (EPA, 2018b)) and in Scenario 1 and Scenario 2 (estimated in this work).

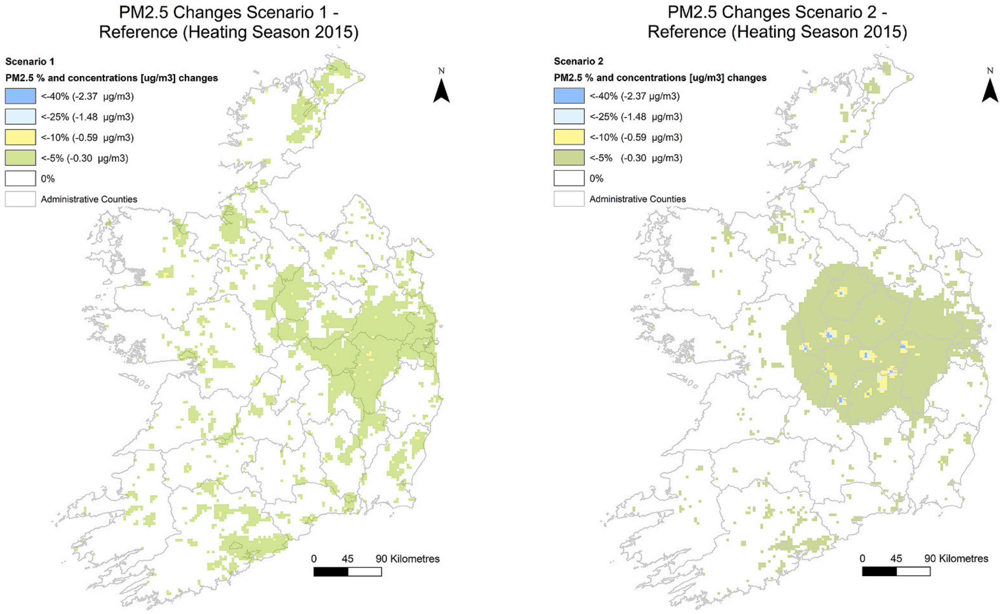


Fig. 10. a and 10b: Modelled changes in surface $PM_{2.5}$ concentrations [$\mu g/m^3$] in the residential sector heating season for Scenario 1 (10a - left hand panel) and Scenario 2 (10b - right hand panel). Both maps show a decrease in simulated $PM_{2.5}$ surface air concentrations (%) between the respective scenario and the 2015 reference for the heating season.

Table 5
Cost of retrofitting to BER B2 per dwelling and per scenario. Note cost of installation of ASHP not included.

BER	Up-front cost to renovate a dwelling up to BER B2 in €	Total cost in Scenario 1 (in '000 €)	Total cost in Scenario 2 (in '000 €)
A1			
A2			
A3	n/a	n/a	n/a
B1	n/a	n/a	n/a
B2	n/a	n/a	n/a
B3	5000	145,825	145,825
C1	15,000	487,305	487,305
C2	15,000	822,855	819,375
C3	15,000	1,212,135	1,074,360
D1	35,000	4,404,610	4,452,210
D2	35,000	2,282,700	2,367,575
E1	45,000		138,105
E2	45,000		46,575
F	50,000		72,650
G	50,000		3750
Total		9,355,430	9,607,730

for those dwellings.

Table 4 shows broadly indicative costs of fabric retrofitting to BER B2 for dwellings that have BER's lower than this. The third and fourth columns give a cumulative cost per level of BER for both scenarios, while the bottom right cell gives a total indicative cost for bringing all of the 388,384 dwellings to a BER of B2. The cost of a deep retrofit, which would bring a home to a minimum of an A3 BER is highly variable, but indicative ranges from €35,000 to €75,000 have been reported (Super Homes Project, 2018). For the purposes of this research, it is conservatively assumed that the costs of renovation up to a B2 would range from €5000 to €50,000 from B3 to G respectively.[17] This is shown in the second column of Table 4. The cost of preparing 400,000 dwellings in Ireland to be ASHP ready, is thus estimated to be in the region of €9.35 billion in Scenario 1 and €9.6 billion in Scenario 2.[18] The scale of the

---

[17] We acknowledge that this is only a very broad indicative approximation, and that across several hundred thousand homes the individual cost profiles may vary considerably within and beyond this range. Period homes in which efficiency measures permissible are limited, are not considered.

[18] Clearly this cost is also delivering on the ambitions to retrofit some 500,000 homes to a level of B2 standard or better by 2030 also.

Table 6
Numbers of dwellings at each BER and per Energy Carrier where ASHP deployed in this work is Scenario 1 (S1) and Scenario 2 (S2).

BER	Oil		Gas		Electric		Peat		Coal		Renewables		Total	Total
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
A1														
A2														
A3	169	169	565	565	171	171	4	4	22	22	5	5	936	936
B1	941	941	1806	1806	277	277	11	11	50	50	30	30	3115	3115
B2	1556	1556	5220	5220	605	605	24	24	93	93	67	67	7565	7565
B3	4782	4782	21464	21464	1988	1988	197	197	479	479	255	255	29165	29165
C1	15659	15659	10945	10945	3720	3720	564	564	1186	1186	413	413	32487	32487
C2	40758	40758			7657	7657	1853	1715	3538	3538	1051	957	54857	54625
C3	65069	65069			5582	5582	2724	413	5976	442	1458	118	80809	71624
D1	125846	125846						955		306		99	125846	127206
D2	65220	65220						1526		713		186	65220	67645
E1								2245		646		178		3069
E2								804		169		62		1035
F								1101		272		80		1453
G								68		4		3		75
Total	320000	320000	40000	40000	20000	20000	5377	9627	11344	7920	3279	2453	400000	400000

premium to make the identified Midlands air pollution hot spots ASHP ready is therefore estimated as approximately €250 million.

A total investment for fabric retrofit and ASHPs of between €13 and €14 billion is therefore estimated for the implementation of Scenario 1 or 2. This will represent a substantial cost for both private and public funds. In terms of existing state supports, it is relevant to note that SEAI provide grants for both fabric insulation and heat pumps.[19] SEAI insulation grants range from €400 euro for attic insulation to €6000 for the insulating of the external walls of a detached house (SEAI, 2020b). A grant of €3500 is also currently available from SEAI towards the cost of purchase and installation of an ASHP (SEAI, 2020a). There are also new “one-stop-shop” models to encourage supply-side engagement in retrofit services supply that can streamline grant processes for consumers and ultimately offer efficiencies of scale in the market with lower transaction costs, that will be vital for driving accelerated uptake rates (Lades et al., 2021). Beyond these partial grant supports, SEAI has also run a “Warmer Homes” funding scheme whereby those who own their own homes but are in receipt of social welfare are offered a free dwelling retrofit (SEAI, 2020c). Ultimately this array of policies and supports will need to be reviewed and refined in order to incentivise and support the strategy presented under Scenario 2. Ensuring that 35–40,000 homes a year to 2030 are made ASHP- ready via retrofitting programmes will amount to a significant acceleration of the progress to date. However, the Government has also articulated a goal to retrofit 500,000 homes to a B2 standard by 2030 in the same 2021 Climate Action Plan. Thus, the relevant ambitions are all aligned and in place, and the clock has started on delivering accelerated annual progress. Operations of substantial scale will now urgently be required to credibly deliver on these ambitions in this timeframe.

Whilst analysing the returns to investment in detail for ASHP investment and determining if the level and format of these grants are adequate for the Irish situation are both relevant considerations, they also lie beyond the scope of this particular paper. Nonetheless, these two topics have been respectively explored in greater detail in this context under earlier research (Kelly et al., 2016; Lades et al., 2021) as a further support to related policy design.

5.2. *Addressing fuel poverty*

It was suspected that the approximately 11,000 dwellings in the Midlands that are contributing to the $PM_{2.5}$ hotspots by their use of solid fuels for heating (See Fig. 3), are also located in areas with higher levels of relative deprivation. Fig. 11 shows a map of Ireland highlighting the HP Pobal Deprivation levels in 2016 at Electoral Division (ED) Level[20] (Haase and Pratschke, 2017)). The index is mapped across six categories ranging from high levels of deprivation to high levels of affluence. The

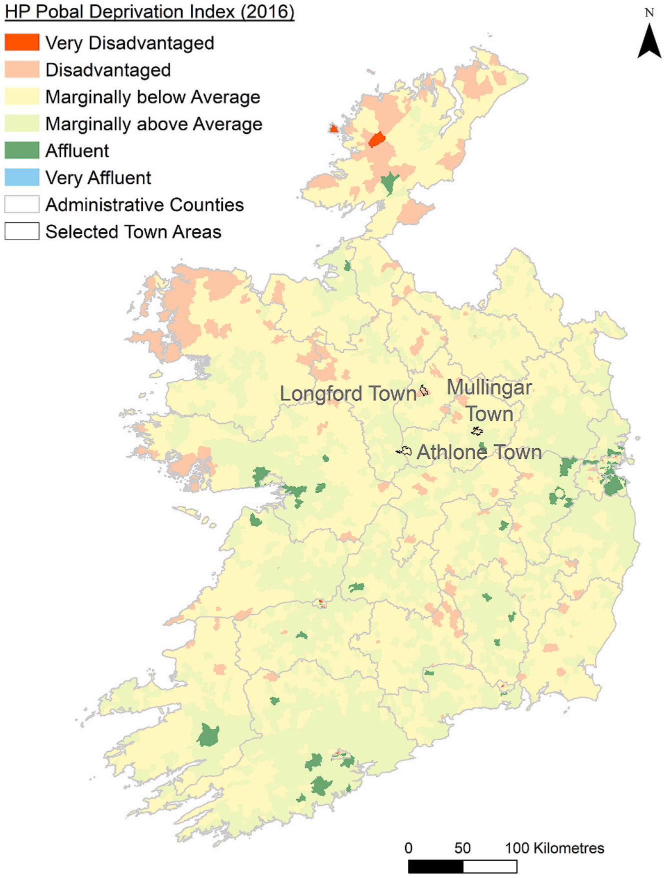


Fig. 11. Authors own map based on Pobal Deprivation Index 2016 at Electoral District Level (Haase and Pratschke, 2017). The 2016 Pobal HP Deprivation Index (Electoral Division Level), accessed at www.trutzhaase.eu.

---

[19] Grants for energy efficiency measures from SEAI are only paid upon completion of work which means that they can contribute to labour costs (Aravena et al., 2016).

[20] The index is based on the combination of three dimensions of relative affluence and deprivation: Demographic Profile, Social Class Composition and Labour Market Situation. There are 3440 legally defined EDs in the State.

red and light brown shading on the map indicate very disadvantaged and disadvantaged areas respectively. The yellow shading represents marginally disadvantaged areas while the light green represents marginally advantaged areas. On a broader scale, most parts of the Midlands fall into either the disadvantaged, marginally disadvantaged or marginally above average categories. Comparing Fig. 3, which shows the midland towns which are air pollutant hotspots, with Fig. 11, it can be observed that for County Longford and County Westmeath, the approximate areas of Mullingar and Longford Town do contain ‘disadvantaged’ shadings but on the other hand Athlone, as a larger and more prosperous town does not. Thus, perhaps some of the solid fuel using dwellings in Mullingar and Longford are in situations of greater deprivation than those in Athlone. Ultimately the granularity of the deprivation index may require further development for this type of assessment. Nonetheless in areas shaded yellow, brown, or red on the map, there is a stronger case that state supports may be needed to support the retrofitting of dwellings to B2 standard. Furthermore, a composite index of energy poverty risk for Ireland, which includes the deprivation index, also highlights areas of the Midlands and West as being most at risk of energy poverty (Kelly et al., 2020). These objective assessments can therefore be used to target and reinforce the case for state supports down to small area level, to ensure the successful implementation of the ASHP roll out in such areas and to track the impact on energy poverty risk.

5.3. Contribution to broader goals, air quality and CO_2 targets

The electrification of residential heating has been prioritised as a core initiative in the national Climate Action Plan (DECC, 2021). Such labour-intensive works have also been highlighted as a central part of the European wide renovation wave (EC, 2020), designed to stimulate economies post-COVID-19, whilst simultaneously driving progress towards ambitious environmental goals. This analysis suggests that on the grounds of GHG emissions abatement, the national heat pump target would clearly make a substantial contribution as detailed in section 4.1. Where solid fuel using homes are displaced with an ASHP it can also deliver reductions in national air pollutant emissions and air pollution concentrations, as detailed in sections 4.2 and 4.3. Beyond this there will also be a substantial opportunity created for a national retrofit industry of scale to develop in support of this ambitious goal to retrofit so many homes in an efficient manner with fabric insulation and heat pumps.

However, in order to realise all of the benefits identified - improvements in ambient air quality, health effects and a just transition - the policy must be spatially targeted. Fig. 12 illustrates the reduction in $PM_{2.5}$ concentrations from all sectoral sources in 2030 in the EPA “With Existing Measures” emission scenario[21] as compared to 2015 (Fig. 2).[22] Decreases in agglomerations of over 1 μg/m^3 can be observed in Fig. 12 across Midland towns and in Dublin City and Cork City. These represent an approximate 20% reduction in $PM_{2.5}$ concentrations over the period and suggest that the residential sector remains a key driver of air pollution hotspots in the Midlands. Scenario 2 as presented in this work has been shown to deliver far better air quality outcomes across these Midland towns, from just the built environment sector, due to the spatial targeting element. In brief, targeting matters.

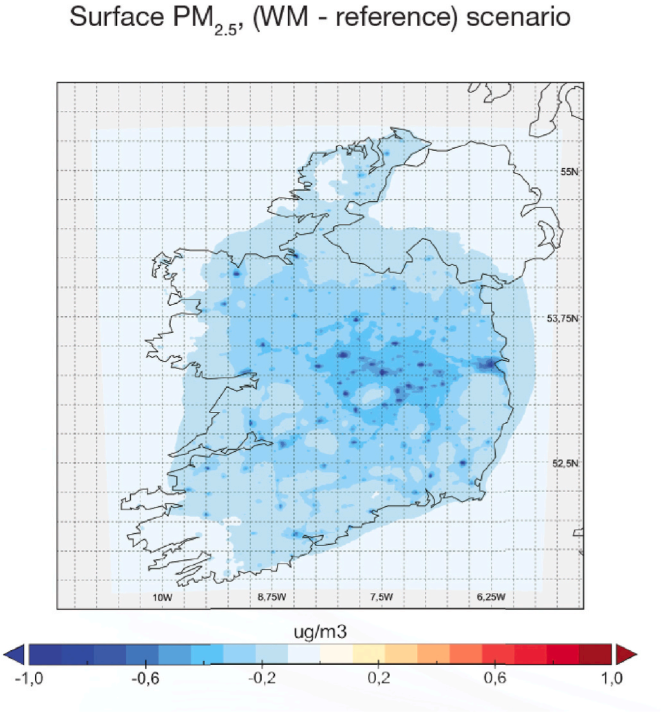


Fig. 12. Modelled changes in surface $PM_{2.5}$ mean concentrations in simulation With Measures relative to the reference (Ó Broin et al., 2019).

6. Conclusion

This work has presented two alternative scenarios for realising the ambition of an Irish Government Climate Action Policy Plan to deploy 400,000 heat pump retrofits by 2030. The findings and method will be relevant to many countries that are prioritising the electrification of residential heating over more carbon intensive and polluting fuels. In the first scenario the heat pumps replace oil, natural gas, solid fuel, and electric boilers across the country without any refined spatial targeting. This delivers substantial reductions in sectoral carbon emissions and air pollutant emissions, with more modest improvements in ambient air quality. The second scenario has shown that by targeting just 3% (11,000) of the ASHP retrofit target into specific Midland towns of Ireland, or similar fine scale locations that may be identified by this methodology, that a number of relative Irish $PM_{2.5}$ hotspots can be eliminated, with consequent benefits for health impacts and the just transition agenda. The supplementary cost of the alternative scenario is estimated to be €250 million greater than a scenario where the ASHP’s are distributed without spatial targeting throughout the country. However, there is great variability in the potential cost of either scenario dependent on the level of supports provided to households, the split between private and social housing action, and the organisational efficiency of any retrofit industry of scale in Ireland. Whilst the approach to financing and supports for retrofitting homes with insulation and heat pumps will require ongoing review and development, this analysis details and quantifies a clear opportunity for policymakers to target an element of this policy action, and in doing so to hit the residential air pollution hotspots whilst supporting a just transition.

Role of the funding source

Funding sources sought no direct influence over the research process, decisions, or findings. The funding only enabled the researchers to

---

[21] The EPA “With Existing Measures” scenario assumes that no additional policies and measures beyond those already in place by the end of the latest national GHG inventory (Ó Broin et al., 2019). In this scenario 175,000 heat pumps are installed to 2030 in line with the 2018 National Development Plan (NDP, 2018) while the number of retrofits continues at the 2018 level which is a combination of the government grant towards Sustainable Energy Authority of Ireland for retrofitting and autonomous retrofitting by householders.

[22] Measuring and monitoring of air pollutant concentrations is improving year on year. In 2019, there were 24 new monitoring stations brought online across Ireland under the Air Quality Monitoring Programme (9 EU standard monitoring sites and 15 ‘local’ monitoring sites monitored in collaboration with local authorities) (EPA, 2020). With a finer resolution, new ‘hot spots’ may arise that are not captured in Fig. 2.

explore the topic so as to inform potential policy design.

Data availability

Key data used in this work can be found at https://eparesearch.epa.ie/safer/the Secure Archive For Environmental Research Data hosted by the Irish Environmental Protection Agency (epa.ie); at https://www.cso.ie/en/census/census2016reports/the database of the Irish National Census of 2016 hosted by the Irish Central Statistics Office (cso.ie); and at https://www.seai.ie/data-and-insights/seai-statistics/key-publications/energy-in-ireland/which are sector based energy use statistics from the Sustainable Energy Authority of Ireland (seai.ie).

CRediT authorship contribution statement

Eoin Ó. Broin: Data curation, Formal analysis, Investigation, Methodology, Roles, Writing – original draft, Writing – review & editing. **J. Andrew Kelly:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Gabriela Sousa Santos:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – review & editing. **Henrik Grythe:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Tove Svendby:** Software, Visualization. **Sverre Solberg:** Formal analysis. **Luke Kelleher:** Data curation, Visualization, Formal analysis. **J. Peter Clinch:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work builds on work from an Irish EPA project - CON+AIR: Addressing Conflicts of Climate and Air Pollution (Ó Broin et al., 2019). The EnvEcon team have been supported by the Department of Environment, Climate and Communications (DECC). The paper is dedicated to the late Prof Martin Williams who was an invaluable member of the CON+AIR Project Steering Committee and who passed away in September 2020.

References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Rafaj, P., Schöpp, W., Wagner, F., 2011. Cost-effective emission reductions to improve air quality in Europe in 2020: analysis of policy options for the EU for the revision of the Gothenburg Protocol.

Anttila, P., Tuovinen, J.-P., Niemi, J.V., 2011. Primary NO2 emissions and their role in the development of NO2 concentrations in a traffic environment. Atmos. Environ. 45, 986–992. https://doi.org/10.1016/j.atmosenv.2010.10.050.

ApSimon, H., Amann, M., Åström, S., Oxley, T., 2009. Synergies in addressing air quality and climate change. Clim. Pol. 9, 669–680. https://doi.org/10.3763/cpol.2009.0678.

AQD, 2008. Directive 2008/50/EC of the European Parliament and of the Council on ambient air quality and cleaner air for Europe.

Aravena, C., Riquelme, A., Denny, E., 2016. Money, comfort or environment? Priorities and determinants of energy efficiency investments in Irish households. J. Consum. Pol. 39, 159–186. https://doi.org/10.1007/s10603-016-9311-2.

Binkowski, F.S., Shankar, U., 1995. The regional particulate matter model: 1. Model description and preliminary results. J. Geophys. Res. 100, 26191 https://doi.org/10.1029/95JD02093.

Brunekreef, B., Strak, M., Chen, J., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bellander, T., Boutron-Ruault, M.-C., Brandt, J., Carey, I., 2021. Mortality and Morbidity Effects of Long-Term Exposure to Low-Level PM2. 5, BC, NO2, and O3: an Analysis of European Cohorts in the ELAPSE Project.

Capizzi, F., Das, A., Dauwe, T., Moorkens, I., Saarikivi, R.J., Tomescu, M., 2019. Renewable energy in Europe - 2019: recent growth and knock-on effects, eionet report - ETC/CME. Eur. Topic Centre on Clim. Change Mitigat. Energy, Belgium.

Carslaw, D.C., Ropkins, K., 2012. Openair—an R package for air quality data analysis. Environ. Model. Software 27, 52–61.

Casquero-Vera, J.A., Lyamani, H., Titos, G., Borrás, E., Olmo, F.J., Alados-Arboledas, L., 2019. Impact of primary NO2 emissions at different urban sites exceeding the European NO2 standard limit. Sci. Total Environ. 646, 1117–1125. https://doi.org/10.1016/j.scitotenv.2018.07.360.

Ciencewicki, J., Jaspers, I., 2007. Air pollution and respiratory viral infection. Inhal. Toxicol 19, 1135–1146. https://doi.org/10.1080/08958370701665434.

Cordell, R.L., Mazet, M., Dechoux, C., Hama, S.M.L., Staelens, J., Hofman, J., Stroobants, C., Roekens, E., Kos, G.P.A., Weijers, E.P., Frumau, K.F.A., Panteliadis, P., Delaunay, T., Wyche, K.P., Monks, P.S., 2016. Evaluation of biomass burning across North West Europe and its impact on air quality. Atmos. Environ. 141, 276–286. https://doi.org/10.1016/j.atmosenv.2016.06.065.

Croft, D.P., Zhang, W., Lin, S., Thurston, S.W., Hopke, P.K., Masiol, M., Squizzato, S., van Wijngaarden, E., Utell, M.J., Rich, D.Q., 2018. The association between respiratory infection and air pollution in the setting of air quality policy and economic change. Ann. Am. Thorac. Soc. 16, 321–330. https://doi.org/10.1513/AnnalsATS.201810-691OC.

Croft, D.P., Zhang, W., Lin, S., Thurston, S.W., Hopke, P.K., van Wijngaarden, E., Squizzato, S., Masiol, M., Utell, M.J., Rich, D.Q., 2020. Associations between source-specific particulate matter and respiratory infections in New York state adults. Environ. Sci. Technol. 54, 975–984. https://doi.org/10.1021/acs.est.9b04295.

DECC, 2021. Climate Action Plan 2021-Securing Our Future. Department of the Environment, Climate and Communications.

Donahue, N.M., Robinson, A.L., Pandis, S.N., 2009. Atmospheric organic particulate matter: from smoke to secondary organic aerosol. Atmos. Environ. 43, 94–106. https://doi.org/10.1016/j.atmosenv.2008.09.055.

EC, 2021. Climate strategies & targets [WWW document]. URL, accessed 11.1.21. https://ec.europa.eu/clima/eu-action/climate-strategies-targets_en.

EC, 2020. A Renovation Wave for Europe – Greening Our Buildings, Creating Jobs, Improving Lives: COM (2020) 662. European Commission.

EC, 2019. The European Green Deal, COM (2019) 640 Final. European Commission.

EC, 2011. A Roadmap for moving to a competitive low carbon economy in 2050, 2011 COM 112. European Commission.

EC, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC [WWW Document]. Httpseur-Lexeuropaeulegal-ContentENALLuriCELEX3A32009L0028. URL, accessed 4.15.21. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028.

EC, 2009b. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

EEA, 2020. Air Quality in Europe: 2020 report. European Environment Agency Publications Office, Luxembourg.

EEA, 2019. Air quality in Europe 2019 — European environment agency [WWW document]. URL, accessed 9.23.20. https://www.eea.europa.eu/publications/air-quality-in-europe-2019.

Electric Ireland, 2020. Installing heat pumps | electric Ireland help FAQ [WWW document]. URL, accessed 4.15.20. https://www.electricireland.ie/residential/help/efficiency/installing-heat-pumps.

Enerdata, 2021. ODYSSEE database [WWW Document]. URL, accessed 4.16.21. http://odyssee.enerdata.net/database/.

EPA, 2020. Air quality in Ireland 2019. Environmental Protection Agency, Ireland.

EPA, 2019. Air quality in Ireland 2018. Environmental Protection Agency, Ireland.

EPA, 2018a. Air quality in Ireland 2017. Environmental Protection Agency, Ireland.

EPA, 2018b. Irish national emissions inventory. Environmental Protection Agency, Ireland.

EPA, 2018c. Irish with measures scenario. Environmental Protection Agency, Ireland.

Fu, M., Kelly, J.A., Clinch, J.P., 2014. Residential solid fuel use: modelling the impacts and policy implications of natural resource access, temperature, income, gas infrastructure and government regulation. Appl. Geogr. 52, 1–13. https://doi.org/10.1016/j.apgeog.2014.04.007.

Fu, Miao, Kelly, J. Andrew, Clinch, J. Peter, 2017. Estimating annual average daily traffic and transport emissions for a national road network: A bottom-up methodology for both nationally-aggregated and spatially-disaggregated results. Journal of Transport Geography 186–195. https://doi.org/10.1016/j.jtrangeo.2016.12.002.

Haase, T., Pratschke, J., 2017. A performance measurement framework for drug and alcohol task forces. Draft final Rep. 36.

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio- respiratory mortality: a review. Environ. Health 12 (43). https://doi.org/10.1186/1476-069X-12-43.

Holst, G., Thygesen, M., Pedersen, C.B., Peel, R.G., Brandt, J., Christensen, J.H., Bønløkke, J.H., Hertel, O., Sigsgaard, T., 2018. Ammonia, ammonium, and the risk of asthma: a register-based case–control study in Danish children. Environ. Epidemiol 2, e019. https://doi.org/10.1097/EE9.0000000000000019.

Hooftman, N., Messagie, M., Van Mierlo, J., Coosemans, T., 2018. A review of the European passenger car regulations – real driving emissions vs local air quality. Renew. Sustain. Energy Rev. 86, 1–21. https://doi.org/10.1016/j.rser.2018.01.012.

Hvidtfeldt, U.A., Chen, J., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bellander, T., Brandt, J., Brunekreef, B., Cesaroni, G., Concin, H., Fecht, D., Forastiere, F., van Gils, C.H., Gulliver, J., Hertel, O., Hoek, G., Hoffmann, B., de Hoogh, K., Janssen, N., Jørgensen, J.T., Katsouyanni, K., Jöckel, K.-H., Ketzel, M., Klompmaker, J.O., Lang, A., Leander, K., Liu, S., Ljungman, P.L.S., Magnusson, P.K.E., Mehta, A.J., Nagel, G., Oftedal, B., Pershagen, G., Peter, R.S., Peters, A., Renzi, M., Rizzuto, D., Rodopoulou, S., Samoli, E., Schwarze, P.E., Severi, G., Sigsgaard, T., Stafoggia, M., Strak, M., Vienneau, D., Weinmayr, G., Wolf, K., Raaschou-Nielsen, O., 2021a. Long-term exposure to fine particle elemental components and lung cancer incidence in the ELAPSE pooled cohort. Environ. Res. 193, 110568 https://doi.org/10.1016/j.envres.2020.110568.

Hvidtfeldt, U.A., Severi, G., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bellander, T., Boutron-Ruault, M.-C., Brandt, J., Brunekreef, B., Cesaroni, G., Chen, J., Concin, H., Forastiere, F., van Gils, C.H., Gulliver, J., Hertel, O., Hoek, G., Hoffmann, B., de Hoogh, K., Janssen, N., Jöckel, K.-H., Jørgensen, J.T., Katsouyanni, K., Ketzel, M., Klompmaker, J.O., Krog, N.H., Lang, A., Leander, K., Liu, S., Ljungman, P.L.S., Magnusson, P.K.E., Mehta, A.J., Nagel, G., Oftedal, B., Pershagen, G., Peter, R.S., Peters, A., Renzi, M., Rizzuto, D., Rodopoulou, S., Samoli, E., Schwarze, P.E., Sigsgaard, T., Simonsen, M.K., Stafoggia, M., Strak, M., Vienneau, D., Weinmayr, G., Wolf, K., Raaschou-Nielsen, O., Fecht, D., 2021b. Long-term low-level ambient air pollution exposure and risk of lung cancer - a pooled analysis of 7 European cohorts. Environ. Int. 146, 106249 https://doi.org/10.1016/j.envint.2020.106249.

Im, U., Christensen, J.H., Nielsen, O.-K., Sand, M., Makkonen, R., Geels, C., Anderson, C., Kukkonen, J., Lopez-Aparicio, S., Brandt, J., 2019. Contributions of Nordic anthropogenic emissions on air pollution and premature mortality over the Nordic region and the Arctic. Atmos. Chem. Phys. 19, 12975–12992. https://doi.org/10.5194/acp-19-12975-2019.

Irish Times, 2020. Home renovation basics: the costs and how to get started [WWW Document]. Ir. Times. URL, accessed 1.11.22. https://www.irishtimes.com/sponsored/ulster-bank/switch-it-up/home-renovation-basics-the-costs-and-how-to-get-started-1.4315719.

Johansson, L., Jalkanen, J.-P., Kukkonen, J., 2017. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. Atmos. Environ. 167, 403–415. https://doi.org/10.1016/j.atmosenv.2017.08.042.

Kelly, A., Chiodi, A., Fu, M., Deane, P., Gallachóir, B.P.Ó., 2017. Climate and air policy in Ireland: synergies and tensions–A GAINS Ireland and Irish TIMES analysis (No. 2013-CCRP- MS.14). EPA report #212. Environ. Protect. Agency. An Ghníomhaireacht um Chaomhnú Comhshaoil PO Box 3000, Johnstown Castle, Co. Wexford, Ireland.

Kelly, J.A., Clinch, J.P., Kelleher, L., Shahab, S., 2020. Enabling a just transition: a composite indicator for assessing home-heating energy-poverty risk and the impact of environmental policy measures. Energy Pol. 146, 111791 https://doi.org/10.1016/j.enpol.2020.111791.

Kelly, J.A., Fu, M., Clinch, J.P., 2016. Residential home heating: the potential for air source heat pump technologies as an alternative to solid and liquid fuels. Energy Pol. 98, 431–442. https://doi.org/10.1016/j.enpol.2016.09.016.

Lades, L.K., Peter Clinch, J., Kelly, J.A., 2021. Maybe tomorrow: how burdens and biases impede energy-efficiency investments. Energy Res. Social Sci. 78, 102154 https://doi.org/10.1016/j.erss.2021.102154.

Lehtomäki, H., Korhonen, A., Asikainen, A., Karvosenoja, N., Kupiainen, K., Paunu, V.-V., Savolahti, M., Sofiev, M., Palamarchuk, Y., Karppinen, A., Kukkonen, J., Hänninen, O., 2018. Health impacts of ambient air pollution in Finland. Int. J. Environ. Res. Publ. Health 15, 736. https://doi.org/10.3390/ijerph15040736.

Leinert, S., Daly, H., Hyde, B., Gallachóir, B.Ó., 2013. Co-benefits? Not always: quantifying the negative effect of a CO2-reducing car taxation policy on NOx emissions. Energy Pol. 63, 1151–1159. https://doi.org/10.1016/j.enpol.2013.09.063.

Liu, S., Jørgensen, J.T., Ljungman, P., Pershagen, G., Bellander, T., Leander, K., Magnusson, P.K.E., Rizzuto, D., Hvidtfeldt, U.A., Raaschou-Nielsen, O., Wolf, K., Hoffmann, B., Brunekreef, B., Strak, M., Chen, J., Mehta, A., Atkinson, R.W., Bauwelinck, M., Varraso, R., Boutron-Ruault, M.-C., Brandt, J., Cesaroni, G., Forastiere, F., Fecht, D., Gulliver, J., Hertel, O., de Hoogh, K., Janssen, N.A.H., Katsouyanni, K., Ketzel, M., Klompmaker, J.O., Nagel, G., Oftedal, B., Peters, A., Tjønneland, A., Rodopoulou, S.P., Samoli, E., Bekkevold, T., Sigsgaard, T., Stafoggia, M., Vienneau, D., Weinmayr, G., Hoek, G., Andersen, Z.J., 2021a. Long-term exposure to low-level air pollution and incidence of chronic obstructive pulmonary disease: the ELAPSE project. Environ. Bar Int. 146, 106267 https://doi.org/10.1016/j.envint.2020.106267.

Liu, S., Jørgensen, J.T., Ljungman, P., Pershagen, G., Bellander, T., Leander, K., Magnusson, P.K.E., Rizzuto, D., Hvidtfeldt, U.A., Raaschou-Nielsen, O., Wolf, K., Hoffmann, B., Brunekreef, B., Strak, M., Chen, J., Mehta, A., Atkinson, R.W., Bauwelinck, M., Varraso, R., Boutron-Ruault, M.-C., Brandt, J., Cesaroni, G., Forastiere, F., Fecht, D., Gulliver, J., Hertel, O., de Hoogh, K., Janssen, N.A.H., Katsouyanni, K., Ketzel, M., Klompmaker, J.O., Nagel, G., Oftedal, B., Peters, A., Tjønneland, A., Rodopoulou, S.P., Samoli, E., Kristoffersen, D.T., Sigsgaard, T., Stafoggia, M., Vienneau, D., Weinmayr, G., Hoek, G., Andersen, Z.J., 2021b. Long-term exposure to low-level air pollution and incidence of asthma: the ELAPSE project. Eur. Respir. J. 57, 2003099 https://doi.org/10.1183/13993003.03099-2020.

Met Éireann, 2022. Temperature - met Éireann - the Irish meteorological service [WWW document]. URL, accessed 1.11.22. https://www.met.ie/climate/what-we-measure/temperature.

Monforti-Ferrario, F., Belis, C., 2018. Sustainable use of biomass in residential sector-a report prepared in support of the European union strategy for the danube region (EUSDR). EUR 29542 EN. doi 10,908058.

NDP, 2018. Irish national development plan 2018-2027 [WWW document]. URL, accessed 9.16.21. https://www.gov.ie/en/policy-information/07e507-national-development-plan-2018-2027/.

Nielsen, O.-K., Plejdrup, M.S., 2016. National mapping of GHG and non-GHG emissions sources: synthesis report for work package 1.

Ó Broin, E., Kelly, J.A., Sousa Santos, G., Grythe, H., Kelleher, L., 2019. CON+AIR: addressing conflicts of climate and air pollution. EPA report #286. Environ. Prot. Agency.

Olsson, D., Johansson, C., Forsberg, B., 2020. Associations between vehicle exhaust particles and ozone at home address and birth weight. Int. J. Environ. Res. Publ. Health 17, 3836. https://doi.org/10.3390/ijerph17113836.

Oudin, A., Bråbäck, L., Åström, D.O., Strömgren, M., Forsberg, B., 2016. Association between neighbourhood air pollution concentrations and dispensed medication for psychiatric disorders in a large longitudinal cohort of Swedish children and adolescents. BMJ Open 6, e010004. https://doi.org/10.1136/bmjopen-2015-010004.

Oudin, A., Segersson, D., Adolfsson, R., Forsberg, B., 2018. Association between air pollution from residential wood burning and dementia incidence in a longitudinal study in Northern Sweden. PLoS One 13, e0198283. https://doi.org/10.1371/journal.pone.0198283.

Raaschou-Nielsen, O., Andersen, Z.J., Beelen, R., Samoli, E., Stafoggia, M., Weinmayr, G., Hoffmann, B., Fischer, P., Nieuwenhuijsen, M.J., Brunekreef, B., Xun, W.W., Katsouyanni, K., Dimakopoulou, K., Sommar, J., Forsberg, B., Modig, L., Oudin, A., Oftedal, B., Schwarze, P.E., Nafstad, P., De Faire, U., Pedersen, N.L., Östenson, C.-G., Fratiglioni, L., Penell, J., Korek, M., Pershagen, G., Eriksen, K.T., Sørensen, M., Tjønneland, A., Ellermann, T., Eeftens, M., Peeters, P.H., Meliefste, K., Wang, M., Bueno-de-Mesquita, B., Key, T.J., de Hoogh, K., Concin, H., Nagel, G., Vilier, A., Grioni, S., Krogh, V., Tsai, M.-Y., Ricceri, F., Sacerdote, C., Galassi, C., Migliore, E., Ranzi, A., Cesaroni, G., Badaloni, C., Forastiere, F., Tamayo, I., Amiano, P., Dorronsoro, M., Trichopoulou, A., Bamia, C., Vineis, P., Hoek, G., 2013. Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). Lancet Oncol. 14, 813–822. https://doi.org/10.1016/S1470-2045(13)70279-1.

Robinson, A.L., Donahue, N.M., Shrivastava, M.K., Weitkamp, E.A., Sage, A.M., Grieshop, A.P., Lane, T.E., Pierce, J.R., Pandis, S.N., 2007. Rethinking organic aerosols: semivolatile emissions and photochemical aging. Science 315, 1259–1262. https://doi.org/10.1126/science.1133061.

Salthammer, T., Schripp, T., Wientzek, S., Wensing, M., 2014. Impact of operating wood-burning fireplace ovens on indoor air quality. Chemosphere 103, 205–211. https://doi.org/10.1016/j.chemosphere.2013.11.067.

Schulze, E.-D., Körner, C., Law, B.E., Haberl, H., Luyssaert, S., 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. GCB Bioenergy 4, 611–616. https://doi.org/10.1111/j.1757-1707.2012.01169.x.

SEAI, 2020a. Heat pump systems [WWW document]. Sustain. Energy Auth. Irel. URL, accessed 4.15.20. https://www.seai.ie/grants/home-energy-grants/heat-pump-systems/.

SEAI, 2020b. Insulation grants [WWW document]. Sustain. Energy Auth. Irel. URL, accessed 4.21.20. https://www.seai.ie/grants/home-energy-grants/insulation-grants/?gclid=Cj0KCQjws_r0BRCwARIsAMxfDRhbFEXMtSHNQyzD9Pcr-BsRUrKmfKKLDoqXV6ByTQtvlGPcspJ738oaAgz8EALw_wcB.

SEAI, 2020c. Free energy upgrades for eligible homes [WWW document]. Sustain. Energy Auth. Irel. URL, accessed 4.21.20. https://www.seai.ie/grants/home-energy-grants/free-upgrades-for-eligible-homes/.

SEAI, 2018. Energy in the residential sector - 2018 Report. Sustainable Energy Authority of Ireland, Ireland.

SEAI, 2016. Energy-related emissions in Ireland - CO2 emissions from Fuel Combustion 2016 Report. Sustainable Energy Authority of Ireland, Ireland.

SEAI, 2013. Energy in the residential sector - 2013 Report. Sustainable Energy Authority of Ireland, Ireland.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyíri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., Wind, P., 2012. The EMEP MSC-W chemical transport model – technical description. Atmos. Chem. Phys. 12, 7825–7865. https://doi.org/10.5194/acp-12-7825-2012.

Sovacool, B.K., Martiskainen, M., 2020. Hot transformations: governing rapid and deep household heating transitions in China, Denmark, Finland, and the United Kingdom. Energy Pol. 139, 111330. https://doi.org/10.1016/j.enpol.2020.111330.

Super Homes Project, 2018. What is Deep Retrofit? 35% grant available in 2020. Superhomes. URL, accessed 4.21.20. https://superhomes.ie/what-is-deep-retrofit/.

UN, 2015. Sustainable development goals: sustainable development knowledge platform [WWW document]. URL, accessed 5.24.20. https://sustainabledevelopment.un.org/?menu=1300.

Vilčeková, S., Nejadkoorki, F., 2011. Indoor nitrogen oxides. Adv. Air Pollut. 31–50.

Williams, M., 2012. Tackling climate change: what is the impact on air pollution? Carbon Manag. 3, 511–519. https://doi.org/10.4155/cmt.12.49.

World Health Organization, 2021. WHO Global Air Quality Guidelines. Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulphur Dioxide and Carbon Monoxide. World Health Organization, Geneva, 2021. Licence: CC BY-NC-SA 3.0 IGO.