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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Exploration of Air Source Heat Pumps for Ireland's Residential Heating Needs
Lead Grantee (Organisation)	University College Dublin
Lead Grantee (Name)	Dr Paula Carroll
Final Report Prepared By	Dr Paula Carroll
Report Submission Date	28th February 2021

	Name	**Organisation**
Project Partner(s)	Dr Pádraig Lyons	ESB Networks
Collaborators	Padraic O'Reilly	Limerick Institute of Technology

Project Summary (max 500 words)

This project reviews the state of the art of research and literature on the use of air source heat pumps (ASHPs) and their operation in temperate climates like Ireland. We identify a gap in the research literature on the efficient operation of ASHPs in residential settings. There is little publicly available empirical data to assess the operation of ASHPs in situ, so researchers and policy makers have to rely on estimates of expected performance from simulated data or from the heat pump manufacturers' technical datasheets. However, the performance in real world settings can differ from testing in laboratory conditions.

We implement a systematic literature review to create a taxonomy of the available ASHP literature, data and models. We design a field study of ASHPs in use in the residential sector and gather ASHP operational data for a sample of 20 deeply retrofitted homes heated by ASHPs with Building Efficient Ratings in the range B2-A2.

We create statistical models of the empirical data to explain the efficiency of the ASHP and to assess ASHP performance. We assess the gap between the observed heat and electricity data, and the expected heat production suggested by the manufacturers' technical operating sheets. We also begin to explore the impact of ASHPs on power quality which we identified as a significant research need to enable the mass adoption of heatpumps.

We summarise the study findings in five peer reviewed academic papers and this final report. We presented the work at two local UCD seminars, two national conferences, and two international conferences.
We find that the ASHPs underperform compared to the manufacturer's expected values. The underperformance is lower at lower temperatures. ASHPs with ratings of 8.5kW (11.2kW) underperformed against the manufacturers expected performance on average by 16 (24)% at outside temperatures of 7°C, and 3 (11)% at outside temperatures of 2°C.
Despite this under performance, the heat produced over the winter heating season is deemed as renewable heat under EU definitions. The Coefficient Of Performance (COP) is the ratio of heat energy produced to the electrical energy consumed. The average or seasonal performance factor (SPF) gives a measure of the ASHP's overall performance by weighting the COP over the days of the winter heating season. The threshold for SPF considered as renewable heat is 2.83. All homes in the sample exceeded the renewable threshold, the average for the sample of retrofitted homes is SPF of 3.08.

Keywords (min 3 and max 10)	Air Source Heat Pump; In-use Field Study; Systematic Literature Review; (Statistical) Models of ASHP Operation.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

This project explores the efficiency of Air Source Heat Pumps (ASHPs) in retrofitted homes in Ireland. ASHPs are part of the solution to decarbonise the residential heating sector. The coefficient of performance (COP) is a measure of efficiency of a heat pump. The heat energy produced by an ASHP is deemed renewable if it meets a specified average COP over the heating season, called a seasonal performance factor (SPF).

Real world operating conditions impact ASHP Performance, Factors such as occupant behaviour, building characteristics and ASHP configuration cannot be fully tested by manufacturers in their laboratories. Heat pump performance in the real world often differs from the expected values specified in manufacturers' datasheets.

This study explores the performance of ASHPs in a sample of 20 deeply retrofitted Irish homes heated by ASHPs. The data were processed to remove homes with significant corrupt or missing data leaving 12 homes for analysis. The homes have Building Efficient Ratings (BER) between B2 – A2. A BER measures the efficiency of a dwelling by calculating the CO2 emissions and KWh/m2/yr.

Exploratory data analysis reveals all 12 houses meet the renewable heat SFP threshold of ≥ 2.83 and therefore qualify as producing renewable heat, the average for the sample is an SPF of 3.08.

However, the performance varied from the manufacturer's expected COP. The study evaluates statistical and machine learning models to predict COP and attempts to quantify the performance gap. ASHPs with ratings of 8.5kW (11.2kW) underperformed against the manufacturers expected COPs on average by 16 (24)% at outside temperatures of 7°C, and 3 (11)% at outside temperatures of 2°C.

The traditional electricity load profile will change as ASHPs are adopted. Low voltage networks are designed to cope with winter heating peak demand. This study also analysed the average winter peak demand for homes heated by ASHPs during periods of extremely cold weather compared to typical winter weather We analyse the average peak, called the after diversity max demand (ADMD), over a group of ASHP heated homes. The ADMD was 3.84 kW and 2.33 kW for extreme cold compared to typical winter weather.

The statistical models created in this study can be used for scenario generation in policy analysis, and can be used in bottom up modelling to assess LV network impacts when wide scale electrification of home heating occurs. The project results are published in academic journal and conference papers.

The project is led by Dr Paula Carroll in the UCD Energy Institute and School of Business, with collaboration from Dr Pádraig Lyons in ESB Networks, and Padriac O'Reilly in Limerick Institute of Technology. The SEAI award is used to fund postdoc Dr Michael Chesser on the study.

2.2 Introduction to Project

This project reviews the state of the art in the research literature on the use of air source heat pumps (ASHPs) and their operation in temperate climates like Ireland. Our study identifies a gap in the research literature on the efficient operation of ASHPs in the field. There is little publicly available empirical data to assess the operation of ASHPs in situ. We implement a systematic literature review to create a taxonomy of the available ASHP literature, data and models.

We access ASHP operational data in a sample of retrofitted homes in the residential sector. We use the empirical data to assess the gap between the observed data and the expected performance suggested by the manufacturers' technical operating sheets. We create statistical models of the observed data to explain the COP, and use our statistical models as the basis for a simulation approach to understand the gap between actual and expected COP performance.

We also begin to explore the impact of ASHPs on power quality, a significant research area identified during our study which is important to support the mass adoption of heatpumps. We summarise the study outputs in academic papers and a final report.

2.3 Project Objectives

Fossil fuels serve 50.5% of the residential sector's energy needs in the European Union. The Republic of Ireland, however is above the European average with 72% of household energy consumption relying on fossil fuels (oil, natural gas & solid fuels).

The Government of Ireland is implementing policies to transition Ireland to a low carbon and environmentally sustainable economy by 2050. Ireland has a renewable heat sectoral target of 600,000 heat pumps by 2030, currently 33,3,000 are installed. Such a high target of heat pumps will not only have a significant effect on electricity demand, but also on the management and operation of the grid.

The objective of this project is to provide a better understanding of the actual efficiency of air source heat pumps in use in the residential sector. The three main objectives are to implement a systematic literature review, implement an ASHP field trial, and to model and analyse the field trial data.

Identifying gaps between the technical operation specifications and the observed ASHP performance allows us to create statistical models so that the actual efficiency can be more accurately modelled. The study aims to understand typical ASHP performance, and to identify and understand data points which deviate from the expected/reference output. These statistical data-driven models can be used in bottom-up approaches to estimate the contribution of ASHPs to electrify heating in Ireland. We also aim to explore the impact of ASHPs on power quality.

2.4 Summary of Key Findings/Outcomes

Having identified the results from published field trials of ASHP performance, we specified the data needed to best model ASHP performance. We accessed ASHP performance and weather data to create statistical models of the ASHP performance. A summary of key outcomes includes:

- *Innovation 1:* Systematic Literature Review

  Summary This published paper[1] presents a systematic literature review of Air Source Heat Pumps (ASHP) field studies. We categorise the papers with respect to the field study focus, and analyse the papers in terms of the field study design, and the analysis methodologies applied to the gathered data. We find three main areas of focus: defrosting management, ASHP system management, and ASHPs as smart grid

[1] Carroll, P., Chesser, M. and Lyons, P., 2020. Air Source Heat Pumps field studies: A systematic literature review. Renewable and Sustainable Energy Reviews, 134, p.110275.

demand response components. We identify what ASHP data is publicly available to assist other researchers in building, testing and analysing ASHP efficiency models. Finally, we identify future research topics on the use of ASHPs in home heating.

- *Innovation 2:* The Impact of Extreme Weather on Electricity Demand from Homes Heated by Air Source Heat Pumps

  Summary This conference paper[2] was presented at the European Conference on Renewable Energy Systems https://www.ecres.net/2020/. We explore residential electricity demand using an innovative dataset from a field monitoring trial of deep retrofitted homes heated by air source heat pumps (ASHPs). We construct the after diversity maximum demand per home during a period of extreme weather to assess the effect on ASHP demand, and the impact of large-scale adoption of heat pumps. In particular we address the research questions: what is the impact of extreme weather on heat pump demand? Which statistical distributions best model the after diversity maximum demand per home heated by an ASHP? Based on goodness-of-fit statistics and criteria, a Gamma distribution best models average coincident electricity demand for homes heated by ASHPs. A more detailed journal paper is in review with the Energy Sources, Part B: Economics, Planning, and Policy.

- *Innovation 3:* Exploration of air source heat pump performance using statistical and machine learning methods.

  Summary This paper[3] was published at the Sustainable Energy Information Technology Conference 2020, A more detailed version if in review in the Energy and Buildings journal. The paper investigates the performance of ASHPs as part of the solution to decarbonise the residential heating sector. The coefficient of performance (COP) is a measure of efficiency of a heat pump. The heat energy produced by an ASHP is deemed renewable if it meets a specified seasonal performance factor (SPF). Heat pump performance in situ often differs from the expected values specified in manufacturers' datasheets. This paper explores the performance of ASHPs in a field trial of 12 deeply retrofitted Irish houses. Exploratory data analysis reveals all 12 houses qualify as producing renewable heat but varied from the manufacturer's expected COP. The paper evaluates statistical and machine learning models to predict

[2] Chesser, M., Lyons, P., O'Reilly, P., and Carroll P., 2020. The Impact of Extreme Weather on Electricity Demand from Homes heated by Air Source Heat Pumps 8th EUROPEAN CONFERENCE ON RENEWABLE ENERGY SYSTEMS, 178-183

[3] Chesser, M., Lyons, P., O'Reilly, P. and Carroll, P., 2020. Probability density distributions for household air source heat pump electricity demand. Procedia Computer Science, 175, pp.468-475.

COP. Generalised additive and Random Forest models were found to provide better in situ COP predictions over linear regression models. The Random Forest model is used to predict COP and compared to the expected COP. ASHPs with ratings of 8.5kW (11.2kW) underperformed against the manufacturers expected COPs on average by 16 (24)% at outside temperatures of 7°C, and 3 (11)% at outside temperatures of 2°C. We use the statistical models to simulate the performance of a sample of 100.000 homes to estimate the effect of large scale ASHP adoption. We find that the average performance over the heating season of 3.08 is above the EU renewable heat threshold of 2.83 and is deemed to be renewable heat.

2.5 Project Impact

Our systematic literature review finds that most ASHP efficiency models rely on simulated data or estimates from the manufacturer's datasheets. Our modelling and analysis of empirical real world ASHP performance data show that the ASHPs underperform against the manufacturer's expected performance This could lead to an overestimation of ASHP performance by policy makers, and an underestimation of the electricity needed by ASHP owners to heat their homes.

The average seasonal performance factor for the sample of retrofitted homes with BER ratings in the range B2-A2 is 3.08. It can be classed as renewable since it is greater than 2.83 which qualifies the heat as renewable energy according to the EU, Directive on the promotion of the use of energy from renewable sources. Each of the 12 homes passed the threshold with SPFs in the range [2.84, 3.36].

Considering the accuracy of the metering equipment, we conclude that that manufacturer's estimates are overstated. Our statistical models of empirical data give more accurate estimates of expected ASHP performance in real world settings.

The estimated average peak demand of the sample homes heated by ASHPs even in extreme weather is below other published estimates based on the Commission for Energy Regulation Smart Meter trial of 2009. While our sample size is small, we can expect our results to generalise to retrofitted Irish housing stock that achieve BER ratings ≥ B2.

2.6 Recommendations

Our statistical models provide more accurate estimates of ASHP performance than manufacturer's datasheets. Our models can be linked to Building Energy Performance modelling and simulation tools, to give a better estimate of real world ASHP performance. Our models, or similar statistical models based on empirical data, should be used to make adjustments in future building simulation tools to provide better data driven estimates of ASHP performance in situ compared to those advised by the manufacturer.

2.7 Conclusions and Next Steps

This use of data driven models is important to better estimate the benefits of ASHP adoption in Ireland's national energy and climate plans. There is a risk that simulation-based approaches that rely on physics based mechanistic models, or the manufacturer's laboratory-based estimates will overestimate the energy savings. Laboratory based or mechanistic models are limited in their ability to capture the effects of the real world factors that influence the ASHP performance such as the occupant behaviours, and home and ASHP configuration.

Our results and analyses are based on a sample of homes with BER ratings in the range B2-A2. We conclude that our finding the heat produced is renewable is indicative of such homes but the generalisability is limited by the small sample size. Our statistical modelling is based on a sample of 20 retrofitted homes, all using the same brand of ASHP, and all located in the same geographical region. As a next step a larger sample across a more representative sample of homes and occupant types could be conducted.

While Covid impacted on our plans and ability to engage with home owners, a more detailed study of the home occupancy under normal societal conditions would be useful to shed insight into occupant characteristics.

Finally, the power quality sub-project is ongoing. Analysis and modelling of the power quality data is the focus of our future work. We aim to assess the impact of ASHP operation on power quality, and to inform low voltage network design and investment needs to achieve the target of 600,000 installed heatpumps by 2030.