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Reducing heat pump installed costs: Reviewing historic trends and assessing future prospects

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HIGHLIGHTS

- We systematically review historic and forecast domestic heat pump installed costs.
- High quality installed cost data is scarce, both in the UK and internationally.
- No reduction found in average installed costs over the past decade in the UK.
- Forecasts suggest significant but relatively moderate cost reductions by 2030.
- Policy support should be resilient to fluctuations in installed costs over time.

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ABSTRACT

Residential heat pumps are a critical energy transition technology, but their installed costs are often much higher than incumbent technologies – imposing a policy imperative, in the UK and elsewhere, to reduce deployment costs. Here, we systematically review historic and forecast UK and international data on heat pump installed costs.

Installed costs are reported using three main metrics: Single Point Cost, Experience Rates and Percentage Cost Reduction. Experience Rates offer the highest quality metric, but there are few available studies, particularly for non-equipment costs. Single Point Cost is the most widely reported metric, but conflates diverse technologies and contexts. Percentage Cost Reduction is a relatively common forecasting metric, but may lack rigour.

Historic data suggests that there has been no significant reduction in the average installed cost of heat pumps over the past decade in the UK, while modest cost reductions were seen internationally. At times, particular countries have aligned deployment growth with significant cost reduction.

Forecast data suggests reductions in installed costs of 20–25 % between 2020 and 2030 in the UK – significant, but relatively modest compared to current UK policy goals. We conclude that heat pump deployment policy support should be resilient to fluctuations in installed costs, as the market grows.

1. Introduction

Many countries have committed to achieving ambitious, economy-wide reductions in carbon dioxide emissions over the next two to three decades. In temperate and colder countries, emissions from domestic heating technologies typically represent a substantial fraction of national totals [1].

Whilst there are a range of technology options available to decarbonise home heating, there is a growing consensus that heat pumps will play a key role. The International Energy Agency has estimated that globally, heat pump installations will need to rise from a current level of less than 20 million per year to more than 100 million per year by 2050 [2]. Heat pump sales are now growing rapidly internationally [3], across both established markets, such as Norway, Switzerland and France, and emerging markets such as Poland and the Netherlands [4,5].

In the UK, domestic heating is dominated by individual gas boilers, and heat pumps are a marginal technology: just 69,000 residential heat pumps were installed in 2022, compared to 23 million UK homes with a

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gas boiler [6,7]. Net zero pathway analysis suggests that heat pumps will need to dominate future installations [8], and the UK Government set a target for at least 600,000 installations annually by 2028 [9] including around 400,000 retrofit installations, with up to 1.9 million installations annually by 2035 [10].

The total lifetime costs of heat pumps are a combination of installation and running costs [11], and there is evidence that, under some assumptions, heat pumps may already be cost competitive with domestic gas boilers on a lifetime cost basis [12,13]. However, their installation costs – the focus of this paper – are much higher, often around three times or more [14].

The UK Government has stated that its ambitions for dramatic deployment growth in heat pump installations are "contingent on the market finding ways to reduce the upfront cost of the systems, while continuing to improve consumer experience and appeal." [9] p57. More precisely, the Government's cost reduction ambitions are to "work with industry to reduce costs of installing a heat pump by 25-50% by 2025 and towards parity between heat pumps and gas boilers by 2030" [9] p86. In addition, the Government aims to rapidly expand the UK's manufacturing capacity and capability, with a 30-fold increase in heat pumps manufactured and sold in the UK by 2030. [9], p.17.

In the context of this urgent policy imperative, we consider the historic evidence and future prospects for heat pump installed cost reduction. We systematically review available data from the UK and internationally on heat pump installed costs, historic and forecast. We also discuss the analytical challenges of assessing heat pump installed costs, the strengths and weaknesses of different cost reporting metrics, the likelihood of realising ambitious near term cost reduction policy goals, and the policy implications of our review findings.

The paper proceeds as follows: the next section outlines our research method, and the methodological challenges of heat pump cost assessment. Section 3 reports findings from our systematic review, compares findings by metric and considers the strengths and weaknesses of different metrics. In Section 4, we discuss our findings in the context of policy aims for cost reduction, particularly in the UK, and also in the wider context of energy technology innovation. Section 5 concludes and identifies policy implications.

2. Research method

2.1. Review methodology

Our systematic evidence review followed protocols developed by the UK Energy Research Centre [15]. The full list of search strings we used can be found in Table A1 in the 'Searches and Data Sources' document, in Supplementary Materials. We searched in Elsevier Science Direct and Scopus, Clarivate Web of Science, Google Scholar, and Google. We also used Google to conduct targeted searches of the specific organisation websites shown in Table A1, Supplementary Materials. No year range restrictions were applied, but all searches were restricted to English language only.

For each search string and database combination, we inspected the first 100 returned results. Where more than 100 results were returned by a search, and we found that directly relevant material was still being found as we approach the 100th result, then we went on to examine the next 50 results to ensure that we captured as much relevant material as possible, within the constraints imposed by the time available. The exception to this was for the searches targeted at specific institutional websites where the first 50 (or in some cases 30) results were inspected.

In total we conducted 37 searches and checked just over 1700 results for relevance, in addition to sources recommended to us and others that the team were already aware of. Returned results were filtered manually for relevance based on their title and abstract. If this was not sufficient to determine relevance, further inspection of the main text was performed. Each document was assigned a relevance rating from 1 to 4, according to the criteria described in Appendix A. This allowed us to subsequently focus our analysis on those documents which were most directly useful. Of the 1704 results checked, 61 were most directly relevant (i.e. were given a relevance rating of 1), with another 120 being at least partially relevant to our research focus (i.e. were given a relevance rating of 2). The full data set (in Excel workbook format) is available in the supplementary materials that accompany this paper.

Over 550 individual cost data points were extracted, across three main metrics:

- *Single Point Cost*: a single installed cost data point published in a specific year. This was the most common metric, with 402 data points drawn from 57 sources. Almost two-thirds (63 %) of Single Point Cost data points are for UK installations.
- *Experience Rate (ER)*: the percentage cost reduction associated with a doubling of cumulative deployment in a specific context. A total of 39 data points from 13 sources were found for this metric. Almost two-thirds of ER data points (62 %) are for non-UK cases, mostly other European countries.
- *Percentage Cost Reduction*: a percentage reduction in heat pump costs between two points in time. A total of 122 data points from 31 sources were found for this metric. Almost three-quarters (72 %) of % Cost Reduction data points are for UK studies.

For each of these metrics, installed cost data may be differentiated by a number of other factors, including: (i) technology type, mainly either air-source (ASHPs) or ground-source (GSHPs); (ii) whether costs were reported as total installed costs, equipment costs, or non-equipment costs; (iii) whether costs were reported as a total value, or on a cost per rated unit of capacity (per kW) basis.

Our review adopted a broadly inclusive approach to data gathering, including domestic scale ASHPs and GSHPs. We focused on air-to-water heat pumps and excluded air-to-air devices, since our concern is those technology types considered likely to dominate the roll-out of domestic heat pumps in the UK.

Our dataset includes existing and new build houses, and for existing buildings, differing levels of building fabric retrofit and heating system upgrades. Given data inconsistencies and limitations (discussed in Section 2.3), we have generally not attempted to normalise the data, other than for exchange rates and inflation. Some specific instances of data disaggregation (for example, between UK and non-UK data) are presented in the Results section.

The original source documents generally either present a single 'typical' installed cost, or high, medium and low values, or costs for a range of different installed archetypes. In cases where single studies offer multiple cost figures according to different assumptions, or sensitivities, we include all values as separate data points.

2.2. Technological background

Installation costs associated with heat pump technologies are contextually sensitive and multi-dimensional. Costs vary widely across different technology designs, building type and other factors, and an individual heat pump cost assessment reflects a series of specific factors: basic technology type and design (e.g. ground source or air source, air-to-air or air-to-water, high or low temperature heat output, with or without hot water provision, monobloc or split unit design, etc.), technical performance and efficiency (often expressed as the coefficient-of-performance (COP) value), ancillary equipment, any associated upgrades to the building fabric or heating system, and non-equipment installed costs, including labour costs.

On average, equipment costs make up around 60 % of total heat pump installed costs, and non-equipment costs around 40 % [13,14,16]. Equipment costs are typically approximately evenly shared between the heat pump unit itself and ancillary equipment (including the buffer tank, hot water tank, emitters (radiators), piping and valves) [13]. On average, labour costs make up around 60 % of non-equipment installed costs, alongside other costs such as design, commissioning, distribution costs and overheads [16].

2.3. Methodological challenges

Assessing heat pump installed costs and cost trends is challenging. One basic problem confronting heat pump installed cost assessment is the limited amount of published data [17,18]. As Weiss et al. [19] p.XIII stated, 'data for heat pump sales are available for many European countries but price data are scarce to non existent'. Published data may also be presented incompletely – for example, without an explicitly stated cost assessment boundary.

In addition, the causes of changing costs are often omitted from published cost assessments, with very few studies relating changing cost to causal factors in specific contexts. This means that published data may only offer a partial, context-specific view, and so caution is needed when comparing studies and collating data.

Another methodological challenge, in terms of interpreting cost trends and cost drivers, is that improvements in heat pump design and performance, possibly driven by tightening regulatory standards, may increase technology costs, at least initially. Potentially cost-increasing technical developments include the integration of more components in the heat pump unit (such as metering, sensors and controls), design modifications to reduce noise emissions, and regulations restricting the types of permitted refrigerants [1,17].

Finally, as heat pumps are deployed more widely across a national housing stock, they will tend to be installed in less suitable building types, incurring additional retrofit costs associated with building fabric or heat distribution upgrades [20].

3. Results

3.1. Single point cost

Fig. 1 presents all Single Point Cost data from our review, combining together historic and forecast data. Reflecting the way most Single Point Costs are reported, the chart shows total installed costs, including equipment and non-equipment costs. Data for equipment costs alone made up a small proportion of the total dataset for this metric, and these data points are not included in Fig. 1; equipment-only average costs historic data show no cost reduction trend over time.[1]

The figure distinguishes between ASHPs, shown as solid blue circles, and GSHPs, shown as solid brown diamonds. GSHPs incur considerably higher installed costs than ASHPs because of the additional costs of trench excavation, borehole drilling and pipework [1].

Total installed costs vary widely, from just under €5000 to just over €30,000. Higher values typically refer to larger GSHP installations, perhaps with significant building fabric and heating system upgrades. Lower values typically refer to ASHPs for new build housing, or retrofits installs which avoid building fabric or heating system upgrades.

On an aggregated basis across all data, total installed costs have been roughly stable since 2010, with only very modest declines in average total installed costs for both ASHPs and GSHPs. Excluding post-2020 data,[2] mean value trend lines suggest cost reductions between 2010 and 2020 of ~5 % for ASHPs and ~ 3 % for GSHPs. In addition, there appears to be no convergence of installed costs over time.

A small proportion of Single Point Cost data is presented as total installed costs per kW, rather than total absolute costs. These data, shown in Fig. 2, show a similar trend as absolute cost data, but with a slight increase in average costs per kW during the 2010s. While for both per installation and per kW data, the overall pattern is approximately stable total installed costs over time, it is unclear why the per installation average decreases slightly over time while per kW data increases. As discussed in Section 2.3, improvements in heat pump design and performance, and deployment in more challenging building types, may lead to increased total installed costs. However, the much greater availability of per installation data suggests this more accurately reflects real experience.

Single Point Cost forecast data are less common than historic reported data. As shown by the trend lines in Fig. 1, available data suggests only modest cost reductions in the 2020s. For ASHPs, the trend line cost reduction between 2020 and 2030 is approximately 9 %; for GSHPs, the trend line figure is ~6 %.

However, because there are relatively few forecast data points, the trend line is weighted towards historic data, and so may underestimate forecasted cost reductions. To better distinguish between historic and forecast data, the dataset can be clustered into time interval groups. Clustered data suggests a more pronounced reduction in average installed costs for ASHPs in the 2020s, of ~24 %. Average ASHP costs reduce from ~€11,000 (~£9500) (2020-29 median average) to ~€8400 (~£7200) (2030-39 median average).[3] For GSHPs the suggested reduction over the same period is much more modest, at ~6 %, from ~€16,700 (~£14,300) to ~€15,700 (~£13,500). Based on very limited data, a more sizeable cost reduction is anticipated for GSHPs after 2040.

While most Single Point Cost data refers to the UK, over one-third refers to 'Rest-of-the-World' (RoW) installations. Disaggregating UK and RoW data suggests a greater reduction in average installed costs internationally than in the UK, particularly for ASHPs. Median average costs in the year ranges 2015-19 and 2020-29 (in practice mostly 2020 or 2021 reported data) reduce by 22 % in the RoW dataset, compared to only 6 % in UK-only data. For GSHPs, there is no equivalent difference between UK-only and RoW data, but this is based on very few data points. In the next section, we discuss the possible causal factors behind differences between UK and RoW data.

3.2. Experience rates

Experience Rates (ERs) are a widely used metric for assessing energy technology costs [21–24]. Also referred to as learning rates, they are often used in energy system modelling exercises, as a way to incorporate technological innovation into future energy scenarios [25].

The ER is calculated as the percentage change in costs for each doubling of cumulative deployment (or number of installations for a standard unit size), based on time series data in a particular context. ER studies may additionally consider the causes of cost reduction – the 'learning effects' associated with deployment – and so can offer useful insights for policy support.

At the same time, there are a number of methodological challenges involved in constructing heat pump ERs, and comparing rates between different studies [17]. Heat pump installations are a 'compound learning system' [22], with distinctive cost and efficiency dynamics for different parts. Heat pump equipment is assembled from standard components (compressor, heat exchanger, electronic controls, etc.) often sourced from international manufacturers and suppliers [1]. By contrast, other installation costs, such as labour costs and building fabric upgrades, vary significantly with context. As Weiss et al. [19] p. XIII stated, 'The functional unit chosen … [for heat pump] experience curve analysis has a considerable effect on the identified rate of cost reduction'.

Jakob et al. [17] suggest that the different aspects of cost and

[1] Olympios et al. (2021) offer a detailed capex-only manufacturer price listing for ASHPs and GSHPs in the UK market; see: https://zenodo.org/doi/10.5281/zenodo.4692648

[2] For illustrative purposes, Figure 1 combines historically reported data and forecast data. However, to calculate historic average cost reductions we generated a trend line based only on historic data.

[3] Although the data intervals span a wide range, most data points fall at the beginning of the 2020s (2020-29 interval) or the year 2030 (2030-39 interval), so the forecast reduction occurs in the 2020s rather than the 2030s.

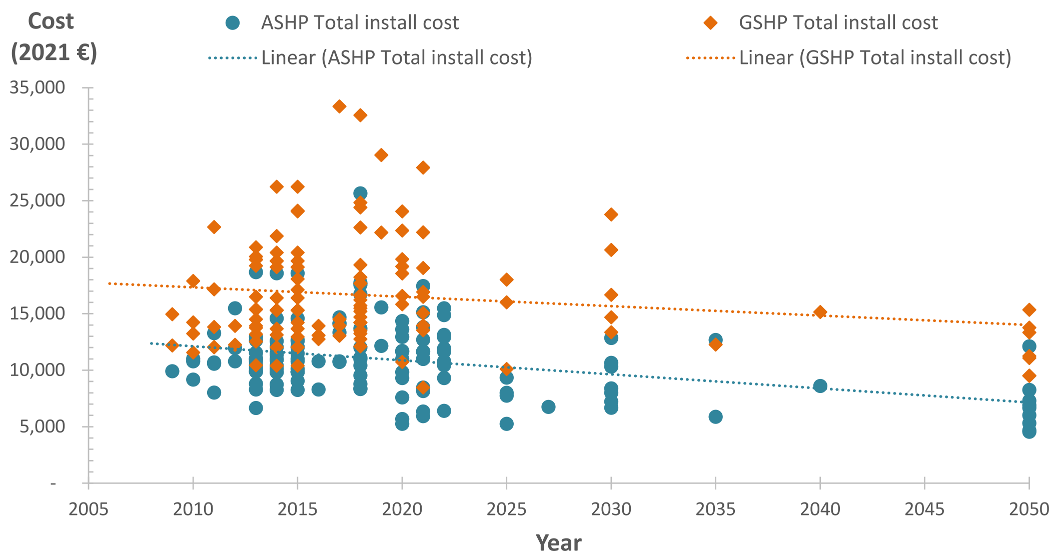

Fig. 1. Single Point Total Installed Costs (per installation data), historic and forecast.

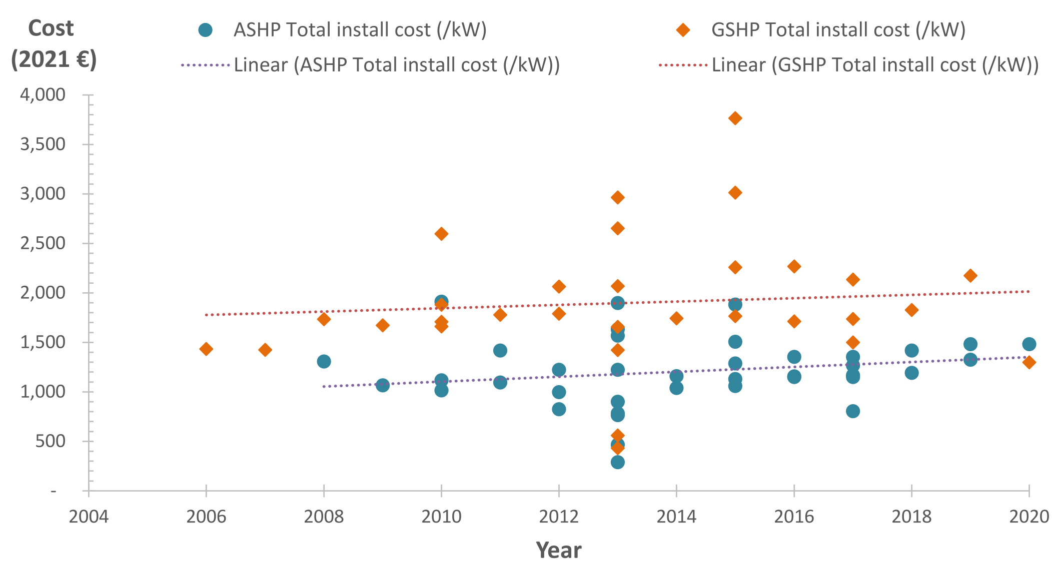

Fig. 2. Single Point Total Installed Costs (per kW data), up to 2020.

learning should be decomposed, but in practice very few published studies include 'multi-factor' ERs for heat pumps. Indeed, confirming other analysts e.g. [17,18], our searches found relatively few heat pump ER studies internationally, with just 13 distinct sources. Although ERs offer a relatively robust way to assess installed cost trends, published data is scarce.

Fig. 3 shows the 32 heat pump ERs in our review. The solid triangles and circles show actual reported rates, drawn from empirical studies of evidence of heat pump costs; hollow markers denote forecast data.

Unlike Single Point Cost data, most heat pump ER data only cover equipment costs: just one-third of available data covers total installed costs. While this reflects a conventional focus in ER studies on technology unit assessment, it omits a high proportion – around 40 % – of total installed costs for heat pumps [14]. ER data may also be inconsistent in terms of whether ancillary equipment costs, alongside heat pump unit costs, are included or excluded. Only four data points in Fig. 3 are reported (historic) studies of total installed costs.

Fig. 3 includes a wide range of reported heat pump ERs internationally, from +35 % to −2.3 %. Of the 32 data points shown, the majority (19) have an ER greater than 10 % – a moderate reduction trend – and six data points have high rates, of over 25 %. However, there are also several cases of much lower rates, with two instances of negative rates – i.e. showing increasing costs with deployment – both for the UK.

Table 1 collates heat pump ER data for four selected countries, alongside deployment figures and analysis of associated causal factors.

Each country case has a distinctive pattern of installed costs, deployment and causal effects:

- *Switzerland* has longstanding experience of heat pump deployment, from the 1980s. Since the mid-1990s, it has combined market growth with substantial reductions in installed costs, with GSHP ERs of ~20 % or above. As well as technical improvements, savings have been enabled by supply chain competition and component importing.

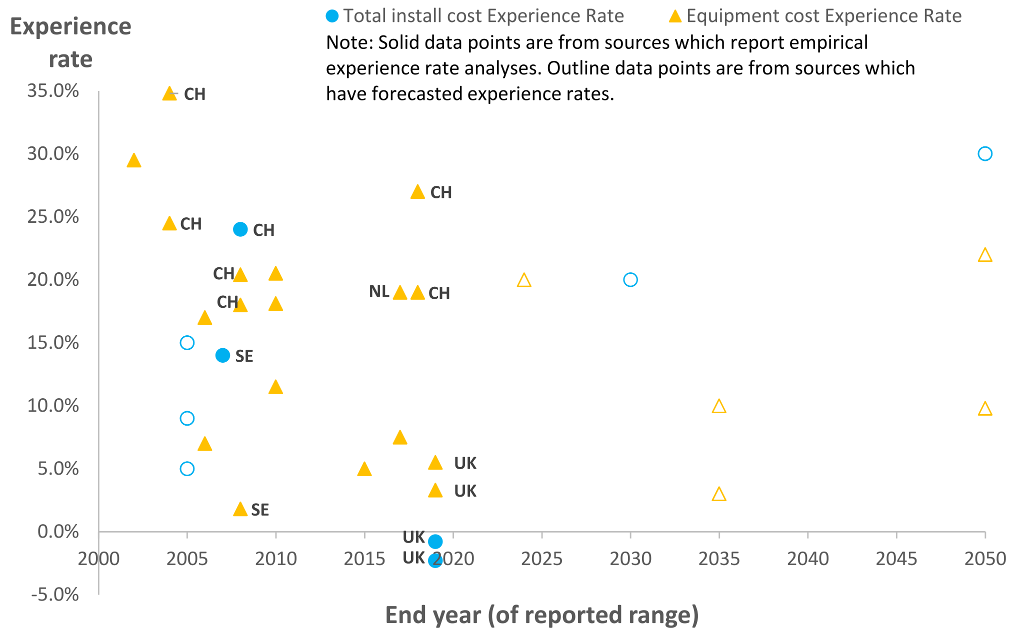

Fig. 3. Experience Rate, by end year of reported range, highlighting selected country specific cases. Country abbreviations: NL: Netherlands; SE: Sweden; CH: Switzerland; UK: United Kingdom.

Table 1
Experience Rates (ERs), Deployment Trends and Causal Factors, selected countries.

Reported ER (%) or Cost Trends	Deployment Trends	Causal Factors
Switzerland		
• 20 % (GSHP, 1982-2008) [26] in [18] • 18 % (GSHP single dwelling, 1980-2008); 27 % (GSHP, multi dwelling, 2012-2018); 19 % (GSHP, combined long term rate) [17] • 25-42 %, varying with unit of analysis; 28 %, combined cost and COP ER (1980-2004) [19] • 24 %, 1991- 2008; [27] (no details provided)	Total annual sales grew from ~4000 p.a. in 1995 to ~26,000 in 2017, mostly ASHP ([17]; [26]). Average growth of 3.3 % p.a., 2010-18 [28]	Market growth has encouraged learning in design, manufacture and installation for heat pump units and wider system components, including smaller and cheaper heat exchangers, improved assembly methods and system integration. Importing of cheaper components from Asia, especially compressors, has also been important. For GSHPs, cost reduction reflects advances in borehole drilling technology, higher equipment use rates and increasing competition from market entrants ([17]; [26]; [19]).
Sweden		
• 1.8 % (GSHP, 1994-2008) [26] in [18] • 2.8 % (heat pump unit); 5.8 % (extended unit) (1991-2020) [29] • 29 % increase in price of GSHPs, 2008-2020 [29] • 14 % (1987-2007) [27] (no details provided)	Total annual sales grew from ~10,000 to ~135,000, 1994-2008; GSHP annual sales rose from ~2000 to 400,001,994-2008; [26] Slower sales growth in 2010s.	Priority on performance improvements (such as the introduction of inverters and advanced controls) rather than cost reduction, in-part driven by regulation (e.g. EU Ecodesign Directive). Limited supply chain competition and importing, reflecting close links between domestic manufacturers and local sellers and installers). A subsidy scheme in the mid-2000s led to price increases because of limited supply capacity ([29]; [26])
Netherlands		
• 19 % (ASHP, air-to-water) (2012-18) • 18 % ASHP (2011-16) (both [17]	Rapid market growth since mid-2010s, from 51,000 total annual sales in 2015 to 118,000 in 2018, and 250,000 in 2020, almost all ASHPs ([28]; [17]; [30])	Learning in manufacturing and installation of both heat pumps and wider system components, including smaller and cheaper heat exchangers, cheaper assembly methods, system integration and importing of components from Asia. Policy support has also been key, particularly a capital subsidy support scheme introduced in 2016 [17]
UK		
• ASHP: 5 % (equipment); −2.3 % (total install costs) • GSHP: 3.3 % (equipment); −0.8 % (total install), 2010-2019 [18] • ASHP install cost has increased by 15 %, from ~£9 k to £10.5 k (2015-2021); GSHP pump install costs approximately stable, ~£20 k [13]	Annual installations rose from 18,500 in 2011 to 31,200 in 2019 and 69,000 in 2022); over 90 % are ASHP, air-to-water [6,31,32]	Policy instability, and taxes and policy costs imposed on electricity (and not on gas) have restricted market growth. Upward cost pressures arise from increasing demand in a historically small market with few qualified installers [18]. Increased ASHP costs are due mostly to non-equipment costs, e.g. more demanding installation requirements, labour, overheads, commissioning and distribution costs [13]

Table 2
Heat Pump Deployment and Installed Cost Reduction, selected countries.

		Cost Reduction	
		Low	*High*
Deployment	*Low*	UK	Netherlands
	High	Sweden	Switzerland

- *Sweden* also has a long history of heat pump deployment, with a gradual building-up of manufacturing and installer expertise, and technological innovation. Although one of the largest markets for heat pumps in Europe, installed cost reduction has been modest, with some increases in GSHP costs in the 2010s. Some evidence suggests that this reflects an emphasis on domestic manufacturing and local supply chains.[4]
- The *Netherlands* has had much less experience of heat pump deployment, historically, but in a supportive policy context, it has seen rapid recent growth in installations, particularly for ASHPs (both air-to-air and air-to-water), which now dominate domestic heating sales for new homes. While evidence is limited, this appears to be associated with significant equipment cost reductions, driven by supply chain competition.
- The *UK* has relatively little experience in heat pump deployment, with some recent market growth. In a historic context of relatively weak policy support and limited deployment, there has been little or no cost reduction or learning in technology development or installation practices. Recent increases in costs, especially non-equipment costs, are reflected in negative ERs.

One overall insight that emerges from the four national cases is that neither market growth nor technology innovation necessarily result in reductions in installed costs. Indeed, conversion efficiency gains and other technological improvements may be prioritised above cost reduction in deployment programmes and policy intent, as the Swedish case illustrates. Renaldi et al. [18] p.8 concluded that "not all progress is translated into cost reduction".

Another insight is that although high ERs tend to be associated with countries with long histories of deployment and the gradual building-up manufacturing capacities and supply chains, such as Switzerland, a substantial equipment cost reduction has also been reported in the Netherlands – a country with much less deployment historically. The caveat here is that the Dutch case is based on a single study, for equipment costs only, and covering less than one doubling of cumulative sales [17]. Table 2 summarises the variety of deployment and cost reduction relationships across the four cases.

There are few published forecasts of ERs for heat pumps. Available data include relatively modest rates, in the range 3–10 % for equipment costs in the UK to 2035 [13], and a high global rate of 30 % to 2050 for total installed costs, although no detail is given [33]. Despite forecasts of very significant deployment growth internationally [1], all forecasted ERs fall within the range of historically reported rates.

3.3. Percentage cost reduction

A third way heat pump installed costs are presented are as a percentage cost reduction figure between two specific dates. Data for this '% Cost Reduction' metric are found for three units of assessment: equipment only (37 % of % Cost Reduction data points), non-equipment costs (22 %) and total installed costs (41 %). This metric therefore provides valuable disaggregated data, as non-equipment costs are rarely reported separately in the other two metrics in our review.

Figs. 4, 5 and 6 show % Cost Reduction data across these three subcategories. Lines on the figures connect data pairs i.e. initial and final year cost points in a single study. As seen with other metrics, % Cost Reduction data span a wide range of values, from +90 % (i.e. a 90 % cost decrease) to −29 % (i.e. a 29 % cost increase). To reduce the 'y axis' range on the figures, the two lowest data values (−29 and − 19) and the single highest data value (+90) are omitted. To reduce the 'x axis' range,

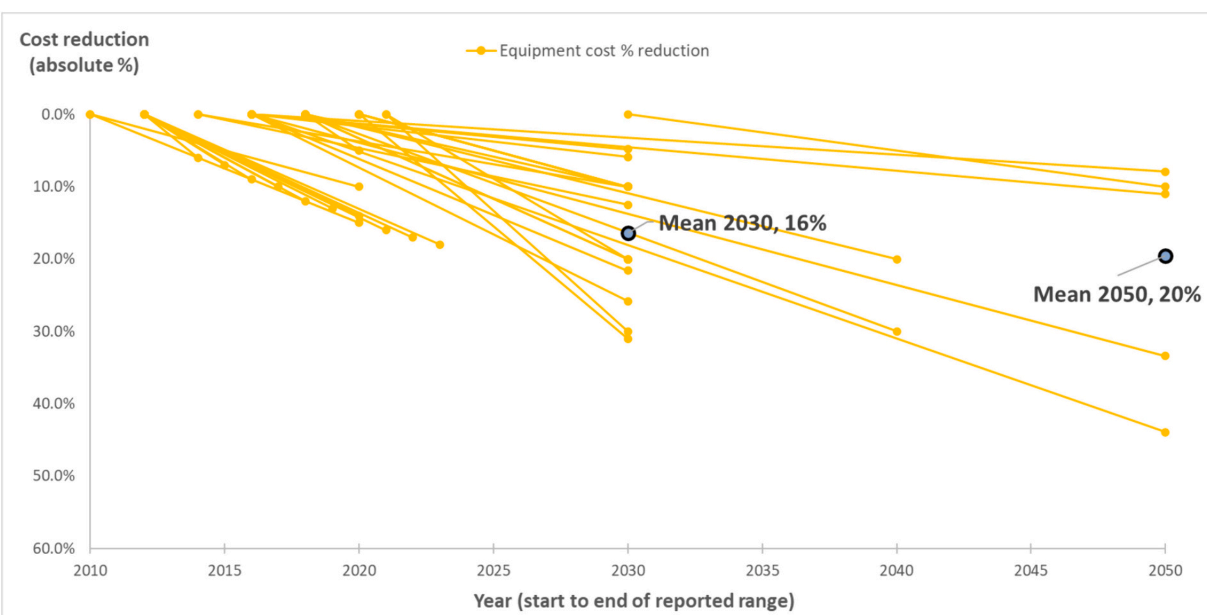

Fig. 4. % Cost Reduction data, equipment costs only.

[4] There is some inconsistency in reported ERs for Sweden, with one study having a significantly positive learning rate, although no details were given [27]. Similar inconsistencies are reported for some other countries, although analytical details are often omitted [27,56].

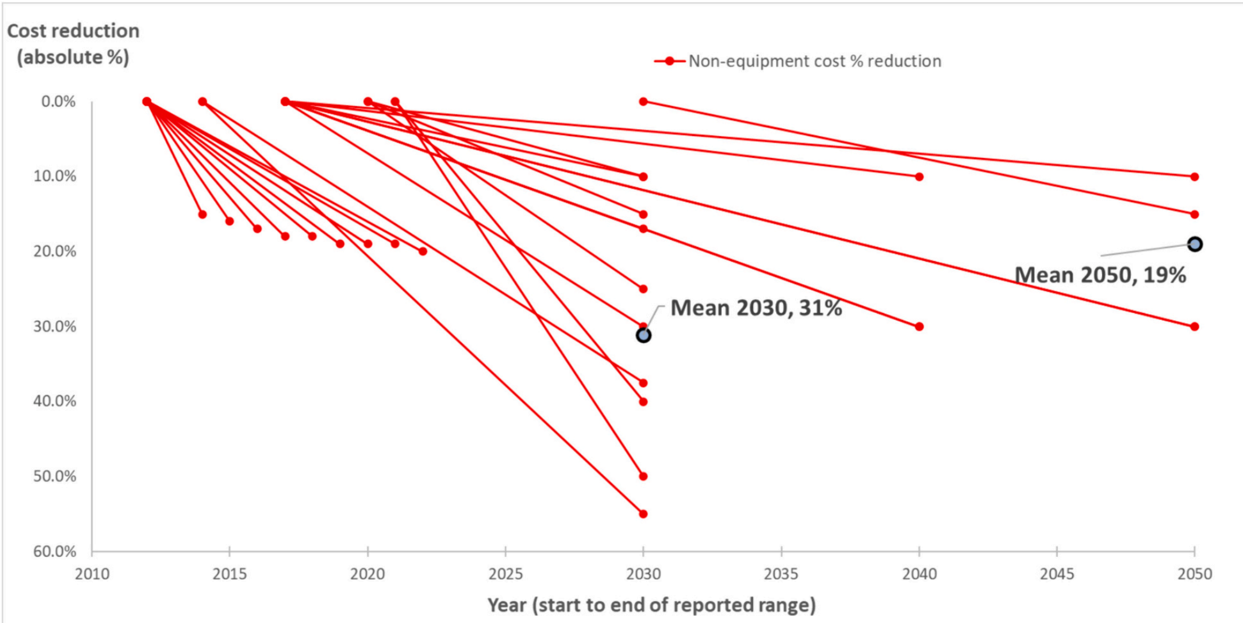

Fig. 5. % Cost Reduction data, non-equipment costs only.

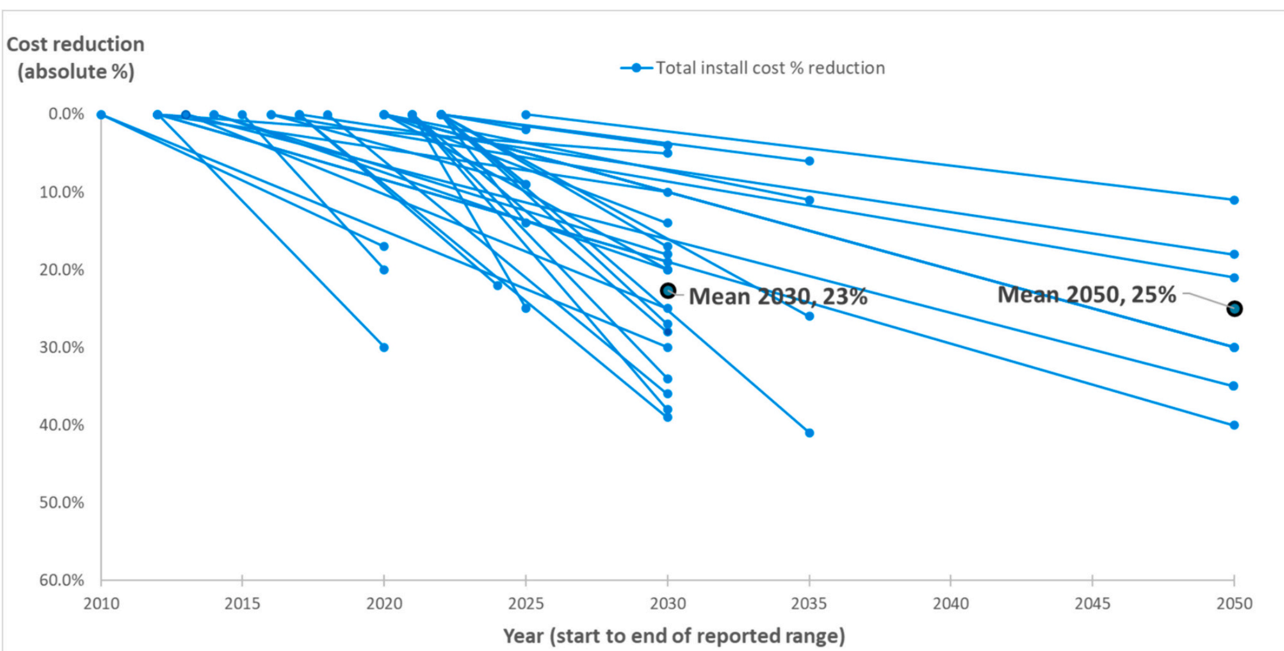

Fig. 6. Percentage Cost Reduction data, total installed costs.

six pre-2010 data points and one 2070 point are also omitted.[5]

The lowest value, for a 29 % cost increase, is for an observed increase in GSHP equipment prices in Sweden between 2008 and 2020 [29]. The only other cost increasing data pair for this metric was for a 19 % observed increase in GSHP total installed costs in the UK between 2006 and 2010 [35]. The same study reported a 22 % decrease in ASHP total installed costs over a similar period. The highest value, a 90 % reduction in costs, is also an observed, historic study, for GSHP equipment costs in Switzerland between 1985 and 2008 [26].

Most % Cost Reduction data are forecasts, rather than historic assessments, and most data (72 %) are from UK studies, so this metric offers a proxy for UK heat pump cost forecasts. Mean values of expected % cost reductions are shown on Figs. 4, 5 and 6, for data pairs with end dates of 2030 and 2050. Data pairs with common end dates may have differing start dates, so the end date average isn't intended to offer an accurate measure of cost reduction over a specific period – rather, it offers an approximate indicator of anticipated reductions over a broadly consistent period. The averages suggest significant installed cost reduction potential to 2030, particularly for non-equipment costs.

With the benefit of hindsight, it is possible to identify discrepancies between % Cost Reduction forecasts and actual observed rates. For example, positive cost reduction forecasts were made for UK heat pump

[5] The omitted data points are highlighted in a data file accompanying the paper.

Table 3
Collated heat pump installed cost data median averages and trends.

	%
Single Point Cost	
Median forecast Single Point Cost reduction, 2020 to 2030, ASHPs (total installed costs)	24
% Cost Reduction[1]	
Median forecast % Cost Reduction, 2030 end point (equipment costs only)	17
Median forecast % Cost Reduction, 2030 end point (non-equipment costs only)	30
Median forecast % Cost Reduction, 2030 end point (total installed costs)	20
Experience Rates[2]	
Median Experience Rate, historic and forecast (equipment costs only)	18
Median Experience Rate, historic and forecast (total installed costs)	14
Experience Rate data range, all data	−2.3 to +35

[1] For consistency across different metrics, Table 3 shows median average % Cost Reduction figures, rather than the mean values shown in Figures 4 to 6.
[2] ER percentage figures represent the % change in total installed costs for each doubling of cumulative installed capacity; ER figures are not directly comparable to % changes in single year or multi-year cost metrics, which may be calculated independently of deployment forecasts.

installed costs for the 2010s [34]. These forecasts were made at a time when ASHP installed costs in the UK had been falling [35]. In practice, ASHP installed costs in the UK increased between 2010 and 2020 [13,18].

This forecast 'error' reflects the multiple factors shaping heat pump installed costs. Rising heat pump costs in the UK in the 2010s have been attributed to limited supply chain capacity, more demanding building contexts and limited deployment in a context of weak policy support [13,18]. Nevertheless, these disparities highlight the possibility of appraisal optimism in cost forecasting, an issue we consider further in the Discussion.

3.4. Comparing cost metrics

Heat pump installed cost data is presented in various formats, reflecting different unit of assessment boundaries and the multiple cost components making up total installed costs. Our review found that installed cost data presented in three main metrics: Single Point Cost, ERs and % Cost Reduction. Table 3 collates average figures for these three metrics.

Comparing results across the three metrics highlights a number of points:

- Heat pump installed costs in the UK have been approximately stable historically, with Single Point Cost data suggesting little or no reduction in reported costs since 2010. By contrast, modest cost reductions have been reported internationally over the same period, and particular countries have, at times, aligned market growth with significantly reduced installed costs.
- There are moderate expectations for future cost reduction. Average forecasts for both single year and % Cost Reduction data – mostly based on UK based ASHP studies – suggest total installed cost reductions of around 20-25 % by 2030; anticipated reductions are higher for non-equipment costs than equipment costs.
- Heat pump Experience Rates vary widely, internationally, from over 30 % to less than 0 %. Average ERs are significantly positive, at 18 % for equipment costs alone, and 14 % for total installed costs. The UK has the lowest reported heat pump ERs internationally.
- The apparent inconsistency between a significantly positive average ER, and the absence of a significant cost reduction trend in historic Single Point Cost data may reflect differences in data origin. Single Point Cost data mostly refers to UK installations, a country with a poor track record of heat pump deployment and cost reduction. In contrast, almost two-thirds of ER data points are from non-UK studies, including countries with strong deployment growth and cost reduction experiences.
- There is an inverse relation between data availability and quality across the three metrics: ER data offer the most robust metric for cost assessment, and in some cases, causal analysis in specific contexts, but this is also the smallest dataset. Single Point Cost data is the largest dataset, but also least consistent, and it includes highly varied technology designs, building types and wider contexts. % Cost Reduction data is a relatively common way of heat pump cost forecasting, but is less robust than ER data. In analysing the prospects for installed cost reductions, the three metrics offer distinct strengths, weaknesses and insights, Table 4.

Table 4
Comparing different installed cost metrics.

Format	Strengths	Weaknesses	Summary Findings
		Single Point Cost	
Historic or forecast Single point cost. Usually for total installed costs, by broad technology type (ASHP or GSHP); less commonly for equipment or heat pump unit costs only. Mix of UK (63 %) and non-UK (37 %) studies	Largest dataset (402 data points). Mostly historic, reported costs, with some forecasts.	Non-normalised dataset, spanning varied technology designs and contexts, so averaging and trend analysis conflates wide variety of technologies and building contexts. Studies may not analyse causal factors.	Wide range of reported installed costs. UK data shows little or no historic cost reduction trend; modest future cost reduction trend, higher for ASHPs. to 2030. RoW ASHP data shows modest recent cost reduction trend.
		Experience Rate (ER)	
ER %, the % change in installed costs for each doubling of total installed capacity. Usually for heat pump unit or equipment only; rarely for total installed costs. Mostly non-UK based.	Based on consistent time series data in a specific place. Some studies offer causal analysis of changing costs, in one or more place contexts. International coverage.	Limited dataset (39 data points), especially for total installed costs. Few detailed studies of causal factors. Very few studies offer disaggregated ERs (e.g. for non-equipment costs).	Wide range of reported and forecast ERs. Most studies show moderate or high rates, including established and emerging markets. Some low rates reported (e.g. UK, Sweden); deployment may not drive cost reduction.
		% Cost Reduction	
% change in cost between two specified dates, usually current and future costs. Mix of equipment-only, non-equipment and total installed cost data. Mostly UK based.	Medium sized dataset (122 data points), including equipment-only and non-equipment data. Data pairs may have consistent contexts and assumptions. Dataset is focussed on UK cost forecasts.	Not based on consistent time series data. May not offer detailed analysis of causal factors affecting costs, and may reflect optimistic or pessimistic assumptions on cost trends.	Wide range of cost reduction forecasts. Average expectations of significant but moderate cost reductions to 2030, particularly for non-equipment costs.

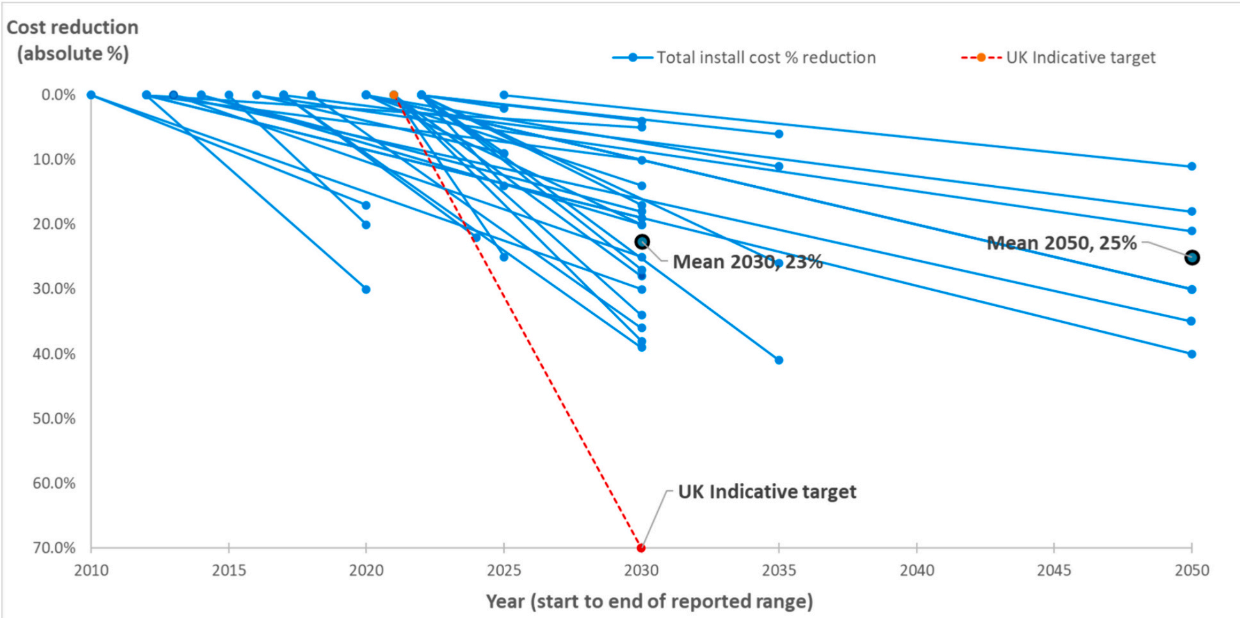

Fig. 7. Heat pump total installed costs % reduction data, including UK policy indicative target.

4. Discussion

4.1. Reflecting on UK policy targets for heat pump cost reduction

Government policy ambitions for heat pump installed cost reduction can be benchmarked against available % Cost Reduction forecast data. The UK Government has declared "an ambition … to reduce costs of installing a heat pump by 25-50% by 2025 and towards parity between heat pumps and gas boilers by 2030" [9] p86. For the indicative analysis presented here we therefore assume a UK policy goal of installed cost parity between heat pumps and gas boilers by 2030.

Total installed costs for domestic gas boilers and heat pumps vary greatly, but reasonable average estimates are ~£3000 for a gas boiler and ~ £10,000 for an air-to-water ASHP [14]. Ignoring any subsidies to help achieve cost parity, such as government grants or loans,[6] achieving cost parity would therefore require a ~ 70 % reduction in total installed costs between 2020 and 2030 – over three times the 23 % mean average % Cost Reduction forecast by 2030 in our review, and well above the highest single forecast of 38 % (Fig. 7).

A heat pump deployment trajectory consistent with the UK Government's target of at least 600,000 installations by 2028 implies ~4 million cumulative installations by 2030 – representing around four market doublings between 2020 and 2030.[7] Achieving a 70 % reduction in installed costs over four doublings in cumulative capacity implies a heat pump ER of around 26 %.[8] This is well above the international average of 14 % in published heat pump ERs (see Section 3.2, above), and slightly above the highest reported rate internationally of 24 % [27] – although less than the highest forecast ER, a long term global estimate of 30 % [33]; see Fig. 8.

This indicative target ER of 26 % to 2030 is set against the UK's poor recent track record of heat pump installed costs. It is also distinct given the short timescale involved, and although a 19 % ER has been reported for the Netherlands for 2012-18 [17], this was for a single study, of equipment costs only. In effect, realising UK Government policy ambitions for heat pump deployment and cost reduction implies a radical change from international laggard to leader, in less than a decade.

4.2. Cost reduction experiences for other energy technologies

Energy transition policy targets have developed in a context of steep cost reductions for some supply technologies, particularly solar PV and windpower. Between 2010 and 2020, the total installed cost of solar PV globally fell by over 80 %, and by over 30 % for both onshore and offshore wind energy [36]. Over the same time period, increases in windpower conversion efficiency and technical performance meant that its total levelised cost, including capital and operating costs, halved [36].

For windpower, the causes of cost reduction have included supply chain competition, scale economies and the development of a virtuous cycle of market growth, investment and innovation [37–39]. For solar PV, cost reduction trends have been observed over decades, with a long term international ER of ~20 % [40]. Since 2010, reduced PV installed costs have been driven by manufacturing scale economies as global production expanded and relocated, and reduced 'non-technology' installed costs [40–42].

Policy support has been a critical enabler of deployment growth, innovation and cost reduction. For onshore and offshore windpower, competitive auctions for revenue support contracts drove supply chain efficiencies in the 2010s [43]. For solar PV, progress has also been driven by revenue support contracts in many countries, and producer subsidies in some major manufacturing countries, particularly China [38,42].

By contrast, costs for some other energy supply technologies, including nuclear power and geothermal, have at times increased [36,39,44]. In explaining different cost trajectories of different technologies, there is evidence that modularity – i.e. a relatively small

[6] From October 2023, the UK Government's Boiler Upgrade Scheme offers capital grants of £7500 for eligible ASHP and GSHP installations, see: https://www.gov.uk/apply-boiler-upgrade-scheme/what-you-can-get

[7] For our indicative analysis, annual installation figures for the period 2021-2030 were generated using an exponential line fit, to represent the gradual development of supply chain capacity in the early 2020s before more rapid expansion in the late 2020s; this is broadly consistent with other analyses [8,57].

[8] For each doubling of cumulative capacity, final installed cost = (initial installed cost x PR), where PR (Progress Ratio) = (1 – ER). For four doublings in cumulative capacity, the PR is the 4th root of the ratio of the final and initial installed cost, which for a 70 % cost reduction is 0.3. The 4th root of 0.3 is 0.74, giving an ER of (1 - 0.74) = 0.26, or 26 %.

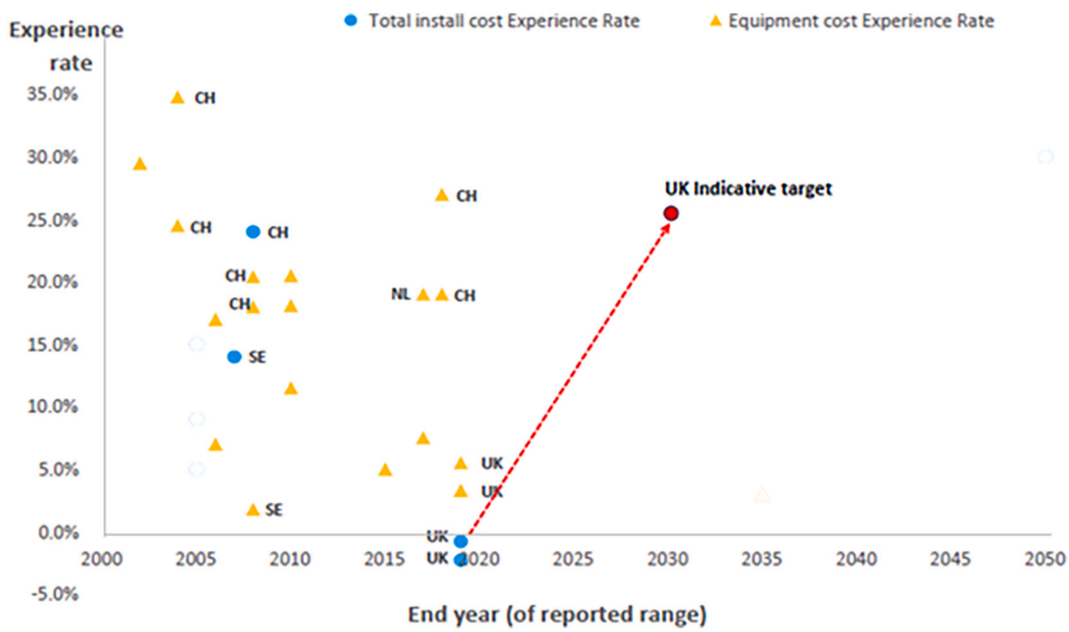

Fig. 8. Experience Rate, by end year of reported range, including UK policy indicative target. Country abbreviations: NL: Netherlands; SE: Sweden; CH: Switzerland; UK: United Kingdom.

technology unit to enable standardisation and replication economies – has been an important factor [45].

However, even for technologies which have shown long term cost reductions, progress has been irregular. In the late 2000s and early 2010s, the installed costs of solar PV and windpower rose, under a combination of rising demand, supply chain bottlenecks, commodity price increases and skills shortages [40,41].[9] Since late 2021, supply chain bottlenecks and commodity price increases have returned, again increasing renewables technology installation costs [46,47].

From a cost forecasting perspective, this means that there have been cases of both 'appraisal optimism', when expectations of cost reductions were confounded and costs increased rather than decreased, but also 'appraisal pessimism' when cost reductions were unanticipated or underestimated. For example, in 2010 offshore windpower costs in the UK were expected to fall only gradually over the following decade [48]. In the event, installed costs fell by almost 40 % by 2020, and levelised costs more than halved [49,50].

4.3. Drawing lessons for heat pump installed cost reduction

Drawing lessons from the experiences of other energy technologies' cost dynamics for heat pumps is not straightforward. Gidén Hember [29] concluded that the windpower case demonstrated that it was possible to reduce prices in parallel with efficiency improvements, and indeed, high expectations for heat pump installed cost reductions among some parts of policy and industry appear to echo cost reduction achievements in other technologies.

According to the UK *Heat and Buildings Strategy,* for example, heat pump cost reduction will be achieved through a combination of market competition, economies of scale and new financing models [9]. Elsewhere, the UK Government has identified 'industrialised' manufacture and supply chain innovation as key heat pump cost reduction drivers [51]. Government consultations with industry have suggested that savings are achievable through modularisation and more efficient manufacturing and installation processes [52].

However, although partly modular, heat pumps are better understood as part-modular technologies with significant installation-specific cost elements. Heat pump technology units are assembled from standard, mature components, many of which are also used in air conditioning units, often in shared factories, by small number of major manufacturers operating in competitive global supply chains [53]. Heat pump assembly plants are more dispersed, including a small number of UK based plants [53].

Internationally, as heat pump supply chains and manufacturing capacities respond to increased demand, scale economies, design standardisation and technological innovation are expected to drive reduced equipment costs [1] – although most equipment cost forecasts in our review suggest relatively modest reductions. As Renaldi et al. [18], that heat pump units are essentially mature, global products with limited scope for further cost reductions.

By contrast, non-equipment costs, which make-up almost half of total installed costs [1] tend to be more nationally and locally specific. Particularly in countries with less mature domestic markets and supply chains, more efficient sales and installation practices, and more capacity and competition in installation, may offer more significant scope for cost savings than equipment cost reductions – as the results from our review suggest.

Finally, experiences from the heat pump sector and beyond also suggests that international ambitions for rapid deployment growth present risks of cost increases, at least temporarily. In the early 2020s, heat pump supply chains and manufacturers have faced increased component costs and capacity shortages [54], and many European countries are experiencing labour shortages related to heat pump installation [1]. Although some of these issues can be ameliorated by policy, others are largely beyond immediate policy influence. Cost increasing 'exogenous factors' affecting energy technologies, such as commodity price changes and exchange rate fluctuations, have at times overwhelmed any positive learning effects [22].

5. Conclusions

For many countries, reducing heat pump installation costs is an energy policy imperative, and the UK Government has set highly ambitious

[9] Although the terms 'cost' and 'price' are often used interchangeably in published data, it is important to distinguish between them in any causal analysis of cost reduction, as prices reflect market conditions as well as underlying cost drivers [22]

near-term installed cost reduction targets. Given this, there is a vital need for an extensive, reliable and transparent evidence base for decision-support – yet we found significant analytical challenges and data limitations in this area. Heat pump installed costs are reported inconsistently and often only partially, across differing technology types, building contexts and assessment boundaries – and access to some data sets is restricted to private firms and industry associations. Therefore, one preliminary finding from our review is an urgent need for improved data quantity, quality and access, with a greater emphasis on total costs, including both equipment and non-equipment costs.

Our systematic review of available data found three main metrics were used for reporting and forecasting heat pump installed costs: Single Point Cost, Experience Rates and % Cost Reduction. Each offers particular insights: Single Point Cost data shows that historic average total installed costs have been approximately static in the UK over the past decade, during a period in which moderate reductions in average costs were seen internationally. Experience Rate data includes some cases of countries successfully aligning deployment growth with sizeable installed cost reductions, but also cases where costs did not reduce despite significant market growth. These contrasting experiences appear to reflect differing levels of emphasis on installed cost reduction as a policy objective. Finally, % Cost Reduction data suggests that, while there are prospects for significant reductions in total installed costs in the 2020s in the UK, these reductions are unlikely to be on a scale and pace to match UK policy targets. In addition, % Cost Reduction data suggest that, as a mature technology, much of the scope for reduced heat pump installed costs lies in non-equipment installation practices and markets.

A number of policy implications follow on from these findings. Firstly, although it is an understandable policy imperative, government goals for dramatic near-term reductions in average installed costs may be unrealistic, especially for countries with limited deployment experience and existing supply chain capacities. In this context, signalling that policy support is contingent on highly ambitious and difficult-to-deliver cost reduction targets may be inadvertently self-undermining, and weaken industry, investor and consumer confidence.

Secondly, international evidence on heat pumps and experiences from other energy technologies suggest that market growth is a necessary but insufficient condition for achieving installed cost reductions. Additional interventions to reduce costs are also needed to grow capacities and foster competition throughout the heat pump supply chain – in component manufacturing, assembly, installation and maintenance – while also safeguarding quality, performance and reliability. Although evidence is limited, international experiences suggest a possible trade-off here between expanding domestic manufacturing and assembly capacities – a declared policy priority in the UK and elsewhere – and achieving rapid market growth at least cost.

Thirdly, international experience of heat pump deployment is now extending to countries such as the UK where heat pumps have hitherto played little role in buildings heating, and where retrofit installations will necessarily make up the majority of installations overall. This offers an emerging evidence base for national government deployment and cost reduction efforts, and setting ambitious but realistic policy goals. For example, both the Netherlands and the UK are aiming to transition rapidly away from gas-based domestic heating, and early Dutch experience, although reflecting local context, offers useful lessons for UK policy support.

It is important that governments, their advisory bodies and independent analysts systematically monitor this accumulating international evidence base, to identify effective and transferable policy interventions. Alongside more conventional measures such as mandates, quotas, loans and grants, the challenges of installed cost reduction suggest a need to redesign the economic case for heat pumps, to better reflect their whole lifetime benefits – such as by innovative rental or heat-as-a-service schemes [55].

Overall, our findings do not mean that ambitious policies to support rapidly rolling-out and significantly reducing installed costs of heat pumps are not desirable. Indeed, well-designed and sustained policy support is a critical enabler of deployment growth and cost reduction, but it cannot guarantee results, especially in the near-term. Given their central role in decarbonising home heating, policy support for heat pumps should be resilient to fluctuations in their installed costs, as the market grows.

CRediT authorship contribution statement

Mark Winskel: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Philip Heptonstall:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Gross:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mark Winskel reports financial support was provided by UK Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The research data has been upload as a MS Excel file, under the heading 'Supplementary Interactive Plot Data, see Appendix B'

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Appendix A. Searches and data sources

Search strings and relevance ratings

The search strings used are listed in Table A1 below, together with the database/search engine that the string was applied to. Where applicable, the targeted organisation is also shown. For the searches of academic journal databases, the searches were restricted to the title, abstract and keywords (or nearest equivalent, if that search option was not provided by a database).

Table A1
Search terms.[1]

Search string	Database/search engine	Targeted organisation
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	ScienceDirect	N/A
"heat pump" AND cost AND (history OR domestic OR home OR house OR household OR building)	ScienceDirect	N/A
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Web of Science	N/A
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Scopus	N/A
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google Scholar	N/A
"heat pump" AND (cost OR history)	Google	N/A
"heat pump" AND "cost reduction"	Google	N/A
"heat pump" AND "learning rate" AND domestic	Google	N/A
"heat pump" AND "experience rate" AND domestic	Google	N/A
"heat pump" AND "learning curve" AND domestic	Google	N/A
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	UK Government
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	Scottish Government
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	Climate XChange
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	CCC
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	National Grid
"heat pump" AND cost	Google	IEA
"heat pump" AND cost	Google	Kensa Heat Pumps
"heat pump" AND cost	Google	Octopus Energy
"heat pump" AND cost	Google	Eunomia
"heat pump" AND cost	Google	Cambridge Econometrics
"heat pump" AND cost	Google	Delta-ee
"heat pump" AND cost	Google	UK Heat Pump Federation
"heat pump" AND cost	Google	UK Heat Pump Association
"heat pump" AND cost	Google	UK Ground Source Heat Pump Association
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	European Heat Pump Association
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	Regulatory Assistance Project
"heat pump" AND ("cost reduction" OR "learning rate" OR "learning curve" OR "experience rate")	Google	Searched by region: Sweden and Switzerland
"heat pump" AND cost	Google	UK National Infrastructure Commission
"heat pump" AND cost	Google	IPPR
"heat pump" AND cost	Google	European Council for an Energy Efficient Economy
"heat pump" AND cost	Google	Energy Systems Catapult
"heat pump" AND cost	Google	Energy Saving Trust
"heat pump" AND cost	Google	CREDS
"heat pump" AND cost	Google	UKERC
"heat pump" AND cost	Google	UKRI
"heat pump" AND cost	Google	IRENA
"heat pump" AND cost	Google	Association for Decentralised Energy

[1] Quotation marks are used for terms with more than one word to denote that the entire specific string will be searched for.

Relevance ratings

Each document was assigned a relevance rating from 1 to 4 according to the criteria described below:
(1) Article shows clear discussion and/or data that is directly focussed on some or all of the research questions.
(2) Article shows clear discussion and/or data that is related to but is not directly focussed on any of the research questions.
(3) Article mentions at least one of the search terms, but is of only limited relevance to the research questions.
(4) Article is found to be irrelevant or duplicate on closer inspection.

Quantitative data sources and metric types

Data sources are listed in the three tables below, grouped by metric type i.e. single year costs, experience rates and percentage cost reductions.

Table A2
quantitative data sources for single year costs.

Citation	Evidence ID code[1]
(AEA, 2012)	GT1, 14
(Arvanitopoulos et al., 2021)	OTH 46
(Bergman and Jardine, 2009)	G3, 9
(Carbon Trust and Rawlings Support Services, 2016)	GT1, 6
(Carbon Trust, 2020)	G2, 5
(CCC, 2010)	GT4, 12
(CCC, 2013)	GT4, 10
(CCC, 2015)	GT4, 8
(CCC, 2019a)	GT4, 6
(CCC, 2019b)	GT4, 7
(CCC, 2019c)	SN12
(CCC, 2020a)	GT4, 5
(CCC, 2020b)	GT4, 9
(Chaudry et al., 2014)	GT24, 1
(Cooper, 2021)	GT11, 1
(Currie & Brown, 2019)	GT4, 3
(Delta Energy & Environment, 2012)	GT11, 4
(Delta Energy & Environment, 2016)	GT3, 2

(continued on next page)

Table A2 (*continued*)

Citation	Evidence ID code[1]
(Delta Energy & Environment, 2018)	OTH 2
(Dicks and Dellaccio, 2021)	GT10, 1
(EHPA, 2013)	GT15, 5
(EHPA, 2014)	G1, 4
(EHPA, 2015)	G5, 5
(Ekström et al., 2018)	SD2, 4
(Element Energy, 2021)	GT4, 2
(Enviros Consulting, 2008)	GT1, 13
(EST, 2021a)	GT22, 1
(EST, 2021b)	GT22, 3
(Fawcett, 2011)	G1, 13
(Foster et al., 2017)	GT1, 4
(Frontier Economics, 2021)	GT18, 2
(GSHPA, 2020)	GT14, 2
(GSHPA, 2022)	GT14, 1
(IEA HPT, 2021)	OTH 66
(IEA, 2020)	G5, 1
(IEA, 2021)	OTH 47
(Ipsos MORI and CAG consultants, 2011)	GT1, 23
(IRENA, 2013)	GT15, 4
(Kensa, 2022)	OTH 59
(Kiss et al., 2013)	G1, 11
(Knobloch et al., 2019)	G3, 4
(Kohler et al., 2018)	G2, 14
(Kokoni and Leach, 2021)	SD2, 10
(Kozarcanin et al., 2020)	GS1, 5
(LCICG, 2012)	OTH 45
(LCICG, 2016)	GT1, 12
(MCS, 2021)	OTH 48
(Octopus Energy, 2022)	GT8, 1
(Osso et al., 2017)	GT20, 2
(Paiho et al., 2017)	SD2, 6
(Pragmatix Advisory, 2021)	G3, 14
(Renaldi et al., 2021)	SD1, 1
(Sissons et al., 2022)	OTH 64
(Sweett, 2013)	GT1, 11
(Wang, 2018)	SD2, 9

[1] An Evidence ID code is assigned to each source document. This code is then associated with every data point extracted from the corresponding source document. This allows every data point in the data file to be tracked back to its original source. The data file has been made available with the paper see Appendix B.

Table A3
quantitative data sources for experience rates.

Citation	Evidence ID code[1]
(Desroches et al., 2012)	G4, 2
(EHPA, 2014)	G1, 4
(EHPA, 2017)	OTH 69
(Jakob et al., 2020)	SD1, 9
(Knobloch et al., 2019)	G3, 4
(Kohler et al., 2018)	G2, 14
(Munuera, 2014)	G5, 8
(Renaldi et al., 2021)	SD1, 1
(Sissons et al., 2022)	OTH 64
(Sweett, 2013)	GT1, 11
(US DoE, 2017)	G4, 3
(Weiss et al., 2010)	SN 32
(Weiss et al., 2008)	G3, 3

[1] See footnote above, Table A2.

Table A4
quantitative data sources for percentage cost reductions.

Citation	Evidence ID code[1]
(Baringa, 2021)	G3, 1
(BEIS, 2021)	OTH 35
(Canada Energy Regulator, 2021)	G3, 19
(CCC, 2010)	GT4, 12
(CCC, 2015)	GT4, 8
(CCC, 2019b)	GT4, 7

(*continued on next page*)

Table A4 (*continued*)

Citation	Evidence ID code[1]
(CCC, 2020a)	GT4, 5
(CCC, 2020b)	GT4, 9
(Cooper, 2021)	GT11, 1
(Currie & Brown, 2019)	GT4, 3
(Danish Energy Agency, 2021)	G3, 7
(DCLG, 2012)	GT1, 22
(EHPA, 2017)	OTH 69
(Element Energy, 2021)	GT4, 2
(Foster et al., 2017)	GT1, 4
(Hardy et al., 2016)	G2, 1
(IEA, 2020)	G5, 1
(Ipsos MORI and CAG consultants, 2011)	GT1, 23
(IRENA, 2013)	GT15, 4
(IRENA, 2018)	GT26, 6
(Kiss et al., 2013)	G1, 11
(Kohler et al., 2018)	G2, 14
(LCICG, 2012)	OTH 45
(LCICG, 2016)	GT1, 12
(RHC, 2013)	G3, 20
(Sissons et al., 2022)	OTH 64
(Sweett, 2013)	GT1, 11

[1] See footnote above, Table A2.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124014.

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