HEAT PUMPS

MYTHOLOGY AND ACTUALITY

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The Global Warming Policy Foundation
Note 43

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Contents

Executive summary

- The economics of heat pumps are driven by the ratio of electricity and gas prices, and the heat pump 'gain' – the units of heat energy emitted for each unit of electricity used.
- Heat pumps are mostly deployed in countries with very cheap electricity.
- In the UK, the electricity:gas price ratio has been increasing for many years, as increasing penetration of renewable energy makes the grid progressively less efficient. The ratio is currently around 4.
- Heat pump gains have been improving, but only slowly. The median for an air-source heat pump is around 2.8.
- Thus, even taking into account inefficiencies of gas boilers, the majority of people will find them cheaper to run than an air-source heat pump.
- Although substantial grants are available to install heat pumps, once the (net) capital cost is taken into account, almost nobody doing so will see an overall payback.
- To assess the overall economic effect of installing a heat pump, the capital cost before grants has to be incorporated into the calculation. If this is done, it is found that no heat pump installation is economic.
- The marginal abatement cost of reducing emissions using a heat pump is over £300/t CO_2, many times more than estimates of the damage caused by global warming.
- Installing heat pumps is therefore a mistake, on every measure.

Introduction

Earlier in 2023, Dr Jan Rosenow, a prominent heat pump advocate, published a series of rebuttals of what he called 'myths' about the technology.[1] He later added a cost comparison against gas boilers.[2] In examining his claims, I hope to provide some context, and thus illuminate some of the issues around heat pumps.

The case for using heat pumps is based around the fact that they can deliver 'free energy', harvested from the environment. Doing so involves expending a certain amount of energy in the first place, but the outputs that can be delivered into the home are several times greater than the inputs. The ratio between the heat energy delivered and the electrical energy expended is called the Coefficient of Performance (COP), the Seasonal Performance Factor or,[3] more colloquially, the 'gain'.[4] I will use the latter expression here.

Since, if heating is ever to be decarbonised, most homes will have to use air- rather than ground-source heat pumps, the latter are outwith the scope of this paper, and references here to 'heat pumps' should be taken as meaning air-source.

Rosenow's ten 'myths'

Myth 1: 'Heat pumps don't work in cold climates'

False. The most heat pumps can be found in the coldest climates. More than half of all households in Norway have one.

Electricity in Norway has, historically at least, been extremely cheap as a result of abundant hydro power. Low prices have encouraged consumers to use electrical heating, and discouraged investment in gas as an alternative fuel; as a result, Norway has little by way of a gas distribution network that customers could connect to.[5] More recently, however, electricity prices there were driven up, as a result of low water levels in hydro reservoirs, and high export demand resulting from the energy crisis. Unable to switch to gas, even more consumers have moved to heat pumps in order to reduce bills.

With temperatures falling so low in Norway, consumers know not to rely on a single source of energy. The Norwegian Statistical Board has reported that 1.2 million Norwegian homes burn wood.[6] There are 2.5 million homes in the country, of which 2 million are houses rather than flats.[7] These figures strongly suggest that most Norwegians who have a heat pump also have a stove as a secondary source of heat for cold weather.

This is borne out by data for the UK. The recent Nesta survey of heat pump users found that 70% of homes that had a heat pump also had a secondary source of warmth, typically a wood-burning stove.[8] This indicates that most heat pump users do not trust them to deliver sufficient heat during a cold snap.

Myth 2: 'Heat pumps don't work in existing buildings'

False. From long-standing research: 'The research results clearly show that heat pumps as heating source function reliably also in existing buildings. As a rule, the units worked flawlessly.' [9]

As with the first 'myth', the framing here is something of a straw man, because it it would be obvious hyperbole to say that heat pumps 'don't work' in existing buildings. The real question is, as his cited source explains, *how well* they work in existing buildings; in other words, what is the typical heat pump gain in existing buildings.

The magic number for heat pump gain is sometimes said to be 3.5.[10] This is because electricity prices (per kilowatt hour) have generally been just over three times those for gas.[11] So unless the gain reaches 3.5, it is cheaper to run a gas boiler.

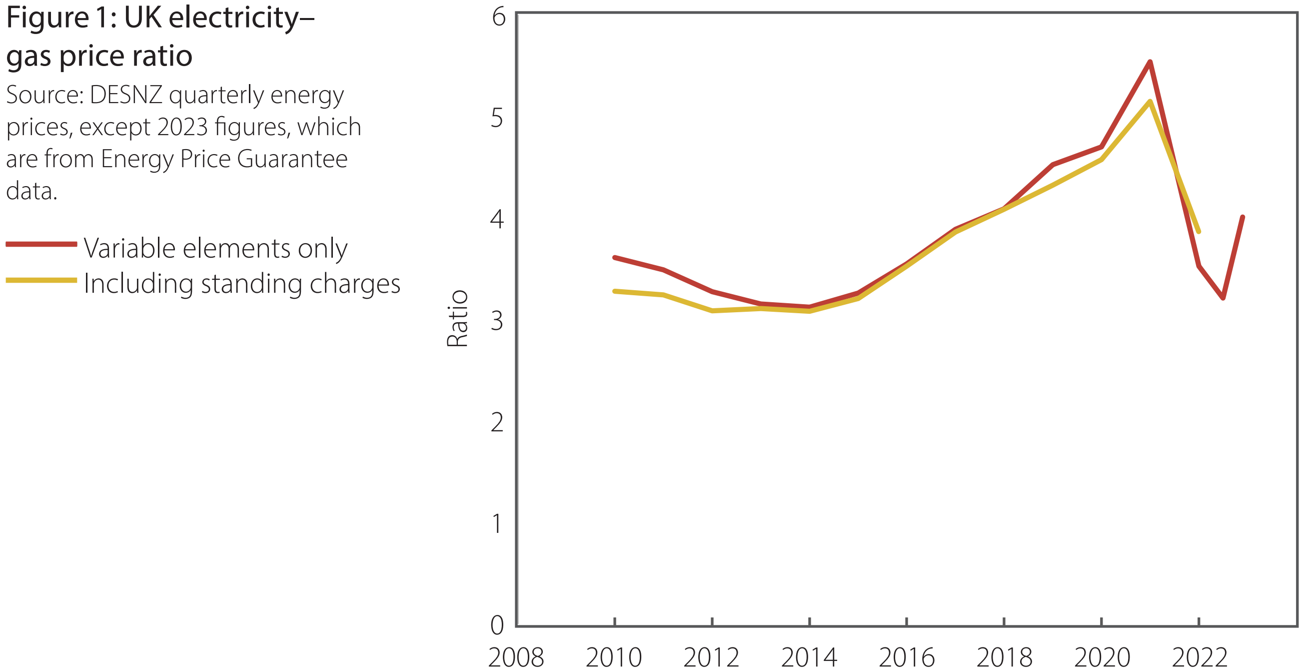
However, in the UK the ratio between gas and electricity prices is now much larger than this, chiefly because renewables have made power generation progressively less efficient (Figure 1).[12] By 2021, before the Ukraine war, it had risen to 5.1,[13] and although the Energy Price Guarantee scheme then reduced temporarily, it is now rising again.

The long-term increase in the ratio highlights an unfortunate issue for heat pump advocates: more and more renewables on the grid are making heat pumps less and less economic.

This effect can also be seen by examining the ratio in different countries. In France, with its abundant cheap nuclear power, the ratio is only 2.4 (and was lower in the past). Similarly, in Sweden, with a mixture of reliable sources, it is as low as 1.1. However, in Germany, which like the UK has a large penetration of variable renewables on its grid, the ratio is 4.1. It is no surprise that Sweden has a lot more heat pumps than Germany.

Figure 1: UK electricity–gas price ratio

Source: DESNZ quarterly energy prices, except 2023 figures, which are from Energy Price Guarantee data.



Rosenow's source, Marek Miara of the Fraunhofer Institute for Solar Energy Systems, finds that in unrenovated buildings, the median heat pump gain was 2.6; for some houses, it was as low as 2.1. This is clearly insufficient to bring any operational savings over gas boilers. The case for heat pumps is strengthened somewhat by a second Fraunhofer study, which used 'smart heat pumps', delivering a median gain of 3.1. The gap with gas may even be narrowed further by taking into account the use of cheap off-peak electricity.

Myth 3: 'Heat pumps don't work in old buildings'

False. There are numerous examples of heat pumps performing well in old buildings.[14]

This 'myth' is similar to the previous one, in that it would be hyperbole to claim that heat pumps 'don't work' in old buildings. Again, the real question is: 'How well do they work?'

Although Rosenow says there are numerous examples of heat pumps working well in old buildings, he gives only one: his own house, a semi-detached villa, perhaps from the early years of the 20th century. He has written about his experiences with converting from gas to a heat pump,[15] highlighting a reduction in energy bills of 60%. Elsewhere, however, he has revealed that the cost of the heat pump itself was £11,500, while he also spent £13,000 on insulation measures.[16] It is clear that his heat pump conversion project was uneconomic and his experience is therefore not generally applicable.

It is worth noting that half of the homes in the Nesta[17] survey were from large modern homes (1996 or later), while only 25% were prewar. Heat pumps seem mostly to be installed in large homes in rural areas, perhaps as an alternative to oil, or even coal, and there may indeed be a case for heat pumps, particularly ground-source, in homes off the gas grid.

Myth 4: 'Heat pumps cost more to run and increase heating bills'

It depends where you are and what your setup is. @IEA produced a handy interactive calculation tool that allows you to explore and compare the economics of different residential heating systems.[18]

While Dr Rosenow seems to be talking about operating costs, the IEA tool he cites calculates a levelised cost of heating, and thus encapsulates both capital and operating costs. The key inputs are user definable, and generally appear reasonable. The gas and electricity prices, in particular, seem representative of those seen in the UK before the Ukraine war, although the gas price is arguably too high.

Using the default values, the calculator shows that gas boilers are 61% cheaper than air-source heat pumps in the UK.[19] However, the default discount rate in the calculator is zero. While academics have sometimes made the case for low or even zero discount rates, in the real world, people discount the future at higher rates. Long-term interest rates are, at time of writing, just below 4%.[20] Using this value in the IEA calculator increases the advantage of gas boilers to 67%.

Moreover, the (unstated) assumption for air-source heat pump gain is 3.[21] The RHPP heat pump survey found that UK heat pump gains are generally rather lower than in other countries, at around 2.4[22] (a source of some discussion among experts). This is well below the level at which operational savings would be made, and far below the level necessary to earn back the capital cost of the heat pump over its lifetime. A more recent but smaller study, from the Energy Systems Catapult, found that the median gain had increased to 2.8;[23] better, but still inadequate.

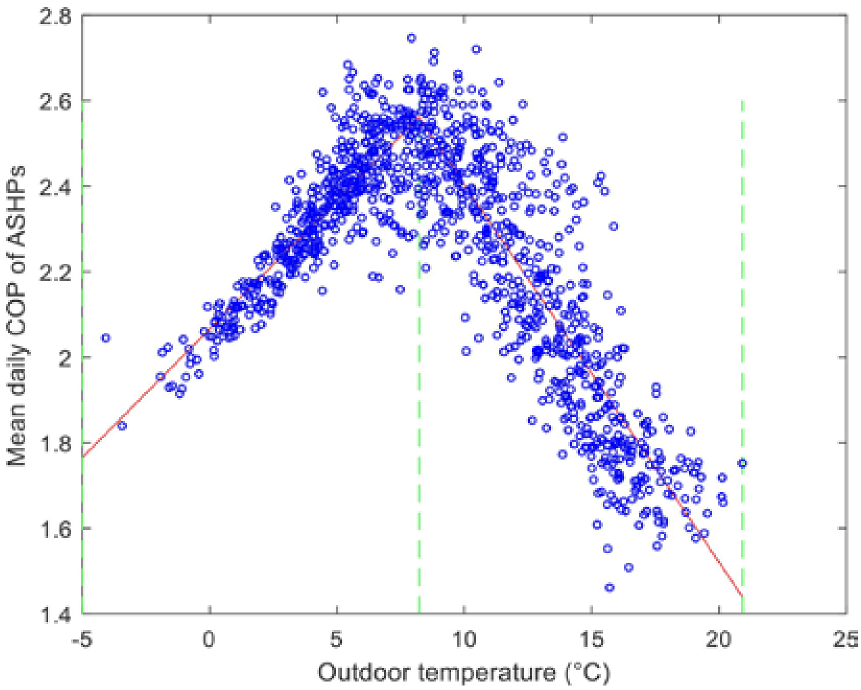
Myth 5: 'Heat pumps are not efficient during cold winters'

Data…shows that heat pump performance during the Beast from the East was good with a [gain] well above 2.[24]

The citation is to a 2018 blog post written by an advisor to Ireland's climate minister. It reports results for 16 houses in Ireland and finds, for outside temperatures below −3°C, an average gain of 2.3. No details of how these properties were selected, or of the heating systems installed, are given. However, Figure 2, based on the RHPP survey data of 14,000 heat-pump equipped homes in the UK, suggests that much lower figures – below 2 – should be expected for the UK at these temperatures.[25] We might expect the detailed data for the Energy Systems Catapult to be slightly better than this, and perhaps as high as 2.2. However, the widespread use of secondary heat sources by heat pump owners speaks volumes.

Figure 2: UK heat pump performance at different termperatures

ASHP, air-source heat pump. Source: Watson et al. 2023.



The blog post reports significant cost savings for air-source heat pumps against oil-fired boilers, but it should be noted once more that these are operational savings only; in other words, the significant capital outlay for a heat pump is not included. The IEA calculator, which does include capital values, finds that air-source heat pumps are 40% more expensive than oil.[26]

Myth 6: 'A heat pump needs to stay on all the time'

You never switch the heat pump off, but this does not mean the heat pump is operating all the time. The system automatically adjusts to outside temperatures and ramps down when it is warmer.

Rosenow's rebuttal is again something of a straw man, because all central heating systems are switched on all the time. But they can be programmed to deliver different heating strategies. For gas boilers, this tends to be either 'warm throughout the day' or 'warm during the morning and evening'.

Heat pumps can be used with different strategies too, but because maximum gains are delivered by underfloor heating, fed with lukewarm water, the strategy adopted tends to be 'warm all the time'. In other words, the most efficient strategy is to try to keep the whole house at a constant temperature throughout the day and night. Watson et al. report that around two thirds of homes with heat pumps adopt such a 'heat all the time' strategy,[27] and find that this is around 20% more efficient than the alternatives on cold days, and marginally so on warmer ones.

Some have cited the discomfort of sleeping in a warm room as a disadvantage of heat pumps. The noise of the pump working throughout the night is also a concern for many (see Myth 9).

Myth 7: 'Heat pumps work with underfloor heating only'

Heat pumps work well with radiators too. In some cases, radiators may need upgrading. But it has been common practice in recent years for heating installers to 'oversize' radiators.[28]

Again, this is a strawman, addressing hyperbole rather than the real question, namely the relative performance of heat pump systems equipped with radiators and underfloor heating.

The RHPP study suggests that around 50% of homes using underfloor heating alongside a heat pump achieve gains of 3 or more. Those using radiators are much more variable, with perhaps only 15% achieving gains above 3.[29] Thus better performance is likely with underfloor heating than with radiators, but an economic return looks implausible either way.

Of course, if a house is not built to modern standards, then extensive insulation and renovation will be required if gains of the order of 3.5 are to be achieved. However, since such works increase the capital cost, doing so puts the possibility of an overall payback even further out of reach; the gains necessary become so large as to be technologically implausible.

Myth 8: 'Heat pumps won't keep you warm'

Households who installed a heat pump report that they are as comfortable or more comfortable than before the installation in survey by @CoolproductsEU 81% have seen the level of comfort improve.[30]

The evidence set out under Myth 1 suggests that most people who have a heat pump also have a secondary source of heat. It is therefore difficult to make objective judgements about comfort levels. However, the ubiquity of secondary sources suggests that a heat pump alone is widely seen as inadequate.

Myth 9: 'Heat pumps are noisy'

Ground source heat pumps make no noise at all. Air source heat pumps can be very quiet as this video shows.[31] ***Also remember: in the summer when you're out in the garden heat pumps usually don't run as no heating required.***

When running, new heat pumps are undoubtedly quiet, as the video linked in the rebuttal makes clear. When operating, they only give off a hum. However, they can rattle when they kick in, just as a fridge does,[32] and this typically happens every ten minutes or so. Meanwhile, in winter, when they defrost themselves, they make a swooshing noise. This can be quite loud.[33] In addition, as an individual heat pump ages, it becomes noisier.[34]

The Nesta study found that around 10% of heat pump users were dissatisfied to some extent with the noise emanating from their appliance. This number is surprisingly high, since only 13% of the users had moved into a house that already had a heat pump; most were presumably therefore relatively new.

Concern over heat pump noise has become sufficiently widespread for the Government to launch a review of the problem.[35]

Myth 10: 'Heat pumps only work in highly insulated buildings'

'Houses do not have to be extensively renovated in order to allow for an installation of a heat pump. Of course, the lower the heat losses, the more efficient a heat pump can operate.'[36]

Again, a strawman, and the rebuttal points to the real issue, which is how efficiently heat pumps will operate with poor insulation. Of course, unless the gain is above 3, there will be no operational savings, and unless significantly so, the capital cost of the heat pump will never be recovered. However, delivering such high gains is impossible without either very high levels of insulation or a very large heat pump, both of which will be very expensive to install. Thus, unless a house is already extremely well insulated, it is unlikely that converting to a heat pump will ever make financial sense.

Myth 11: 'Turning gas to electricity to heat via a heat pump is less efficient than burning gas in a boiler'

False. At [a gain of] 3 a heat pump, even if running 100% on gas electricity, needs ~1/3 less gas to make the same amount of heat than a boiler.

Whether this is a 'myth' depends on what is meant by 'efficient'. If it means the efficiency of total resource use – in other words, the overall cost – then, as we will see in the next section, it is not a myth at all. However, Rosenow's rebuttal suggests that he is only talking about gas usage.

Unfortunately, even if this is the case, his calculations are incorrect, because he has neglected the energy losses in the power station, which are around 50%.[37] In addition, as we have seen, a gain of 3 is not what is observed in practice. Correcting both these figures gives an overall efficiency of 135% for the heat pump as compared to 92% for a condensing gas boiler (Table 1).[38]

Table 1: Gas-use efficiencies

	Input units	Energy losses	Heat pump gain	Output units	Efficiency
Heat pump	100	50%	2.7	135	135%
Gas boiler	100	8%	–	92	92%

Rosenow's cost estimates

In a Twitter thread in April 2023,[39] Rosenow claimed that 'Efficient heat pumps are cheaper to run than gas boilers', his estimate based on the energy price guarantee levels applicable at the time.[40] This was based on calculations of an operating cost comparison of the two technologies, with the operating costs of heat pumps apparently falling below those of (very) inefficient gas boilers at a gain of around 2.5, and below efficient ones at 2.7.

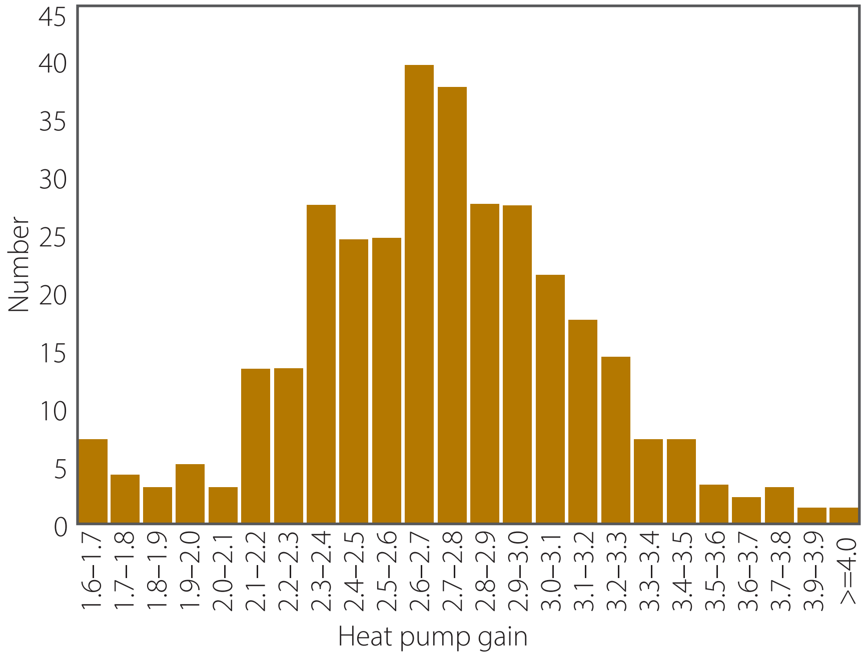
Using data from the Energy Systems Catapult survey (Figure 3), we can see that the majority (71%) of people replacing old boilers with a heat pump would see lower annual bills. For those thinking of replacing a modern efficient boiler, the case is less clearcut, with only around half (55%) seeing lower bills.

Rosenow also concluded that, with capital outlays included, a heat pump would break even with a gas boiler at a gain of 3.4–3.7 (depending on boiler efficiency). The ESC survey data shows that 92% of heat pumps fail to reach the bottom of this range. This means that even on Rosenow's own estimates, almost anyone installing a heat pump should not expect it to pay for itself, although he does not draw this conclusion himself.

There are some problems with Rosenow's calculations (see Appendix), particularly on the operating cost side. However,

Figure 3: Histogram of annual heat pump performance

H4 boundary. Data: Energy Systems Catapult survey 2023.



once corrected, the broad conclusion remains approximately the same; *nobody* should expect an air-source heat pump to pay for itself.

What is worse, the marginal cost of reducing carbon dioxide emissions using heat pumps can be shown to be well over £300/tonne,[41] far more than the £100 that would represent a generous estimate of the cost of the damage done by a tonne of carbon dioxide (the so-called 'social cost of carbon'. This means that heat pumps are uneconomic even when taking into the effects of climate change.

Conclusion

The myths that Dr Rosenow purports to have debunked turn out on the whole to be nothing of the sort. Oversimplification of subtle technical cases does nothing to clarify, and brings heat rather than light to the debate. I hope that by considering these arguments in more detail I have done a better job.

It is clear from the figures presented here that air-source heat pumps are currently uneconomic and, the gap with gas boilers is becoming wider with each year that passes. This will be yet another blow to the Government's net zero drive, but it is an unavoidable consequence of their obsession with renewable energy.

There is little that they can do to change this trend. They might, in the short term, shift levies from electricity onto gas bills, reducing the electricity/gas ratio somewhat; at most to about 3.[42] Improving heat pump technology might help too.[43] But all the while, the ever-growing penetration of renewables onto the grid will tend to erode away these benefits. The conclusion is unavoidable: air-source heat pumps are incompatible with wind power.

Appendix

Operating costs

The operating cost figures should be simple to calculate. The equation is:[44]

Annual cost = (Heat demand × fuel price)/gain

Rosenow cites the April–June 2023 figures for the Energy Price Guarantee scheme, which are:

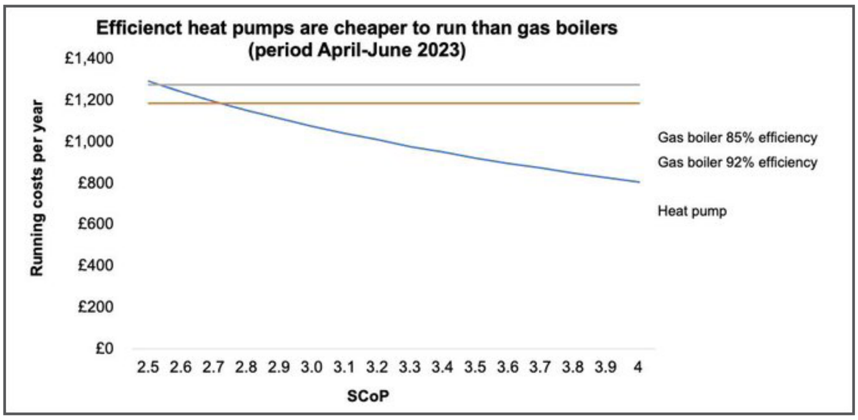
- Electricity: 31.61p (33p including VAT)
- Gas: 9.82p (10p including VAT).

He gives the efficiencies of the boilers as (a) 85% or (b) 92% depending on efficiency, and the heat pump gains are his controllable variable. Earlier in the thread, he gives a gas demand figure of 12,100 kWh.

From his graph (Figure 4), an 85% efficient boiler and a heat pump with a 2.5 gain have almost the same operating cost, at around £1300 per year. However, this does not match the assumptions given; not only are the the resultant numbers off Rosenow's scale (even if VAT is omitted), but the values are very different.[45] I have reached out to Dr Rosenow, who indicates that the crossover is actually nearer 2.6. Measuring the position using a graphics package, it appears to be 2.54, and the equivalent figure for a 92% efficient boiler is at 2.73.

Figure 4: Rosenow's graph on operating costs

The term SCoP (seasonal coefficient of performance) is equivalent to 'gain' in this document.



However, the point at which an 85% efficient boiler has the same cost as a heat pump can be calculated precisely, using simple algebra. If the two annual costs are equal:

$$(d \times f_{HP})/g_{HP} = (d \times f_{GB})/g_{GB}$$

where d is the demand for heat, f is the fuel price, and g is the gain. Assuming demand is the same on both sides of the equation, we can rerrange to give:

$$g_{HP} = \frac{f_{HP}}{(f_{GB}/\, g_{GB})}$$

$$g_{HP} = \frac{0.316}{(0.098/0.85)} = 2.7$$

The equivalent figure for a 92% efficient boiler is 3.0. These figures are nothing like Dr Rosenow's; it is possible he is showing the lines for an 80% efficient boiler rather than a 92% efficient one; the mismatch between the labels on his chart and the lines themselves supports this suspicion, but it is hard to be sure without knowing what value he is using for heat demand. Earlier in the thread, he mentions a figure of 12,100 kWh, but that would give much higher values than the figures on his chart – off the scale in fact.

Dr Rosenow's figures appear incorrect. The reality is that around half of people switching from (very) inefficient (85%) gas boilers would see an operating cost decrease, but only around a third of those switching from efficient (92%) ones.

However, there is a further problem with his analysis. Homes equipped with heat pumps actually use 7% *more* heat than those with gas boilers, as a result of different usage patterns – they tend to be left on 24 hours per day during the heating season because of their low operating temperatures.[46]

Applying this 7% adjustment, we get a revised conclusion that 32% of those switching from inefficient gas boilers and only 17% of those switching from efficient ones would see reductions in running costs.

A further complication is the treatment of standing charges. Since Dr Rosenow's figures already appear too low, it is unlikely that they have been included. However, a household that dispensed with gas central heating could potentially lose the gas standing charge completely, assuming it was willing to use an electric hob. Factoring this into the equation leads to figures that are much more promising for heat pumps, with operating cost reductions being seen by 46% of those switching from inefficient boilers and 30% of those switching from efficient ones.

Full costs

For the full-cost comparison, Rosenow has given a second graph (Figure 5). He says:

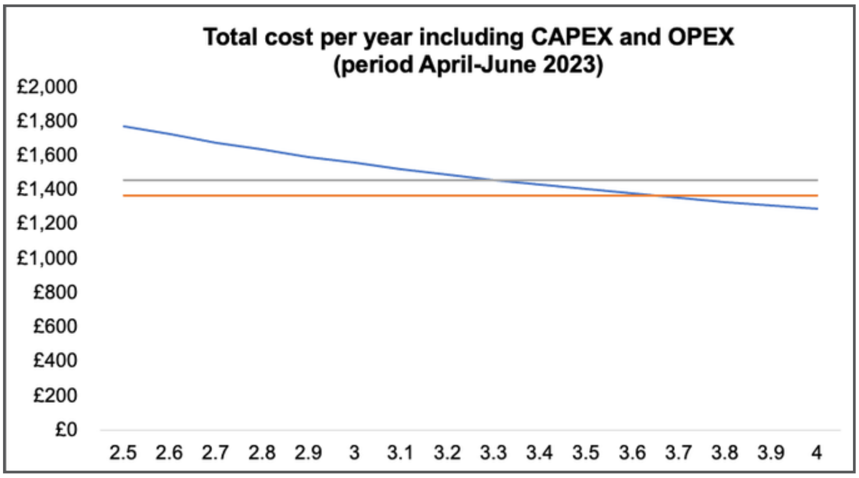
> If we add in the capital cost and assume a 15 year lifetime you would need an [gain] of 3.4-3.7 to break even with a gas boiler depending of the efficiency.

If the lower end of this range is suppose to represent an old-inefficient boiler, then it is rather spurious, since the choice facing consumers is whether to switch to a more efficient gas boiler or a heat pump. Moreover, only 2% of the heat pumps in the Energy Systems Catapult survey acheive a gain of 3.7. This observation was, perhaps unsurprisingly, not made by Dr Rosenow!

It is worth checking the numbers anyway, at least for the comparison against an efficient boiler. The annual cost for heat pumps has risen from around £1400 to around £1800. He suggests that this increase is produced by simply dividing the capital cost over a 15-year lifespan, so we can determine an approxi-

Figure 5: Rosenow's total cost graph

There is no key on the original graph, although it is fairly obvious which line is which. Blue, heat pump; grey, gas boiler (85%); orange, gas boiler (92%).



mate heat pump cost of £7500 (there is no VAT on heat pumps). This is not unreasonable assuming the boiler replacement grant of £5000 has been applied, but to assess the true economic value, of course, the gross cost of £12,500 should be used. It is also worth noting that it assumes that underfloor heating and so on have already been installed.

The values for the boilers, meanwhile, have increased by £150 per year or more. Assuming the same lifespan, the input assumption is that the cost will be perhaps £2500, which would equate to around £2000 plus VAT.

I assume that the 12,100 kWh figure mentioned by Dr Rosenow is for heating only, consistent with the literature,[47] and that total heat demand (including hot water) for a heat-pump equipped home is 30% higher,[48] and I then apply the 7% reduction for houses using gas boilers. In fact, though, only the latter number affects the gain figures outlined below.

Using the capital figures above (net of grant for the heat pump), including VAT where applicable, but not considering standing charges, and with a modest discount rate of 2%, my equivalent values for the gain necessary to give an overall return against an efficient gas boiler is 3.7, the same figure as Dr Rosenow. Again, this level of performance is achieved by few of the heat pumps in the survey. We can safely conclude therefore that, for the vast majority of people, switching to an air-source heat pump is a poor choice.

If we want to assess the true economic efficiency of heat pumps, we need to use a heat pump capital cost figure *before grants*. As already noted, this would be £12,500. In these circumstances, a gain of around 4.6 would be necessary, and none of the 353 heat pumps in the Energy Systems Catapult survey come close to this. We can therefore also conclude that air-source heat pumps are economically inefficient.

Notes

1. https://twitter.com/janrosenow/status/1492086853159301121.
2. https://twitter.com/janrosenow/status/1648688018402713605. See number 16 and 17.
3. Writers on heat pumps sometimes also refer to the seasonal performance factor which is the average gain over a year. The coefficient of performance is strictly a momentary measure.
4. There are various measures of the gain, depending on what electrical inputs are included. The most commonly discussed measures are H2, which can be thought of as including just heating the home, and H4, which includes electricity used for hot water production, and is generally considered the most relevant for cost comparisons to gas boilers. See discussion in SJ Rees and R Curtis, 'National deployment of domestic geothermal heat pump technology: observations on the UK experience 1995-2013'. *Energies* 2014; 7(8): 5460–5499. I use the H4 boundary throughout, and assume that Rosenow is doing the same.
5. https://www.iea.org/articles/norway-natural-gas-security-policy
6. https://norwegianscitechnews.com/2018/04/wood-stove-affects-climate-think/
7. https://www.ssb.no/en/bygg-bolig-og-eiendom/bolig-og-boforhold/statistikk/boliger
8. https://media.nesta.org.uk/documents/Heat_pump_user_survey_report_May_2023.docx.pdf
9. https://blog.innovation4e.de/en/2021/03/03/how-well-do-heat-pumps-really-work-in-existing-buildings/
10. https://housingevidence.ac.uk/the-great-heat-pump-mystery-wheres-the-cop/
11. The Energy Saving Trust reports that as at April 2023, gas cost 10.3p/kWh, while standard rate electricity was 33p/kWh.
12. Data from Quarterly Energy Prices, Tables 2.2.1 and 2.3.1. https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics.
13. In 2021, before the start of the Ukraine war, it had risen to 5.1, before the various government price fixing schemes pushed it back to 4.0 in 2022.
14. https://twitter.com/janrosenow/status/1404720616687689732
15. https://foresightdk.com/how-we-reduced-our-energy-bills-by-60/
16. https://twitter.com/janrosenow/status/1503691026338357253
17. The Energy Saving Trust reports a unit price for oil of 9.2p/kWh, compared to 10.3p for gas. https://energysavingtrust.org.uk/about-us/our-data/
18. https://www.iea.org/data-and-statistics/data-tools/residential-heat-economics-calculator
19. Levelised cost is £111 for an air-to-water heat pump and of £69 for a gas boiler, in each case, translating the USD figure in the calculator to GBP at a rate of 1.25.
20. https://data.oecd.org/interest/long-term-interest-rates.htm
21. François Briens, IEA, pers. commun.
22. At the H4 boundary. See: R Lowe et al. *Final Report on Analysis of Heat Pump Data from the Renewable Heat Premium Payment (RHPP) Scheme*. UCL Energy Institute, 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/606818/DECC_RHPP_161214_Final_Report_v1-13.pdf
23. Again, at the H4 boundary. https://es.catapult.org.uk/news/heat-pumps-shown-to-be-three-times-more-efficient-than-gas-boilers/?reportDownload=https://es.catapult.org.uk/wp-content/uploads/2023/03/EoH-Interim-Heat-Pump-Performance-Data-Analysis-Report-1.pdf
24. https://www.linkedin.com/pulse/how-did-beast-from-east-affect-heat-pump-performance-paul-kenny/
25. Cited in SD Watson et al. Predicting future GB heat pump electricity demand. *Energy & Buildings* 2023; 286: 112917.
26. At 4% discount rate.

27. SD Watson et al. 'How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials'. *Energy & Buildings* 2021; 238: 110777.

28. https://t.co/ScnKPD29br

29. J Love et al. *Investigating Variations in Performance of Heat Pumps Installed via the Renewable Heat Premium Payment (RHPP) Scheme*. UCL Energy Institute, 2017. See Figure 3-12. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/606829/DECC_RHPP_160428_On_performance_variations_v20.pdf

30. https://t.co/3WGVwBWhvQ

31. https://www.youtube.com/watch?v=GKDF5a47eJk&t=1s

32. https://diyhomecomfort.com/blog/heat-pump-noises

33. https://www.youtube.com/watch?v=wudLk0WoIVo

34. https://www.youtube.com/watch?v=jcxy6gW4gXc

35. https://www.homebuilding.co.uk/news/heat-pump-defra-review

36. https://t.co/zXDldES0zC

37. 49.9% per DUKES 5.10. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094465/DUKES_5.10.xlsx

38. This is the figure used in the IEA calculator. François Briens, IEA, pers. commun.

39. https://twitter.com/janrosenow/status/1648688018402713605

40. April–June 2023. These can be seen at https://www.gov.uk/government/publications/energy-price-guarantee-regional-rates/energy-price-guarantee-regional-rates-april-to-june-2023.

41. In brief, I use the carbon intensity of the UK Grid per DUKES 2022 (198g/kWh) for electricity carbon intensity, and Dr Rosenow's figure of 183g/kWh for the gas equivalent. I estimate a levelised cost of heating for heat pumps and the two types of gas boiler, and then simply work out the change in emissions and the change in cost at the heat demand levels outlined in the main text. I do not consider embedded emissions.

42. £10bn of subsidies removed from 330 TWh of electricity demand amounts to a price reduction of 3p/kWh, from 32p to 29p. Adding it to 860 TWh of gas demand amounts to a price increase of 1p/kWh, from 8p to 9p. The ratio thus becomes (29/9) = 3.2. That said, it is questionable whether a government-imposed 15% increase in gas prices would be politically sustainable.

43. One ground source heat pump manufacturer is claiming to be able to deliver gains of over 6. Even allowing for some commercial 'puff', this is the kind of level that would probably provide an economic return. See https://thermia.com/products/ground-source-heat-pumps/thermia-atlas/

44. Which is effectively a loss for gas boilers.

45. They would give:

Gas = 0.098 × 1.05 × 12400/0.85 = £1501

HP = 0.316 × 1.05 × 12400/2.5 = £1645.

46. Heat pumps are typically run constantly. SD Watson et al. 'How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials'. *Energy and Buildings* 2021; 238: 110777. The paper reports a figure of 8% higher heat demand for heat pumps in general. Dr Watson advises (pers. commun.) that the figure is 7% for air-source and 10% for ground source.

47. See ttps://www.beama.org.uk/static/1a84100d-8fae-4208-9f9fa3e07dee1f1a/UK-homes-Analysis-of-kWH-gas-consumption-for-heating.pdf

48. SD Watson et al. 'How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials'. *Energy and Buildings* 2021; 238: 110777

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