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The multiple benefits of current and potential energy efficiency policies: A Scottish islands case study

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ABSTRACT

Energy efficiency is essential for decarbonisation targets, but quantifying its multiple benefits remains difficult given heterogeneity of technologies, stakeholders, and interactions. This study uses a 100%-sample, hourly model to estimate electricity demand and economics for the Scottish islands by 2045. Scenarios of current and more ambitious policies for appliances, buildings, heating, transport and industry are compared. The framework allows assessment of annual demand, peak demand, and average household bills changes which could either increase or decrease depending on policy commitment. Although improving building efficiency can contribute, heat pumps have by far the greatest benefit in reducing bills, annual demand, and peak demand (both daily and maximum winter demand). Increased peak heating and vehicle demand highlights the importance of flexibility. Historic rates of policy achievement will result in significantly increased electricity demand, which could further stress already constrained networks. Although upfront costs are high, most measures have favourable rates of return and all have positive NPVs relative to current electricity prices. Policies to support these costs and distribute the benefits to households, businesses and the energy system will be crucial. As the model only considers changes in technologies, results are likely optimistic given potential rebound effects which could increase demand.

1. Introduction

Achieving net zero targets will require changes across all sectors, of which energy efficiency has been a generally over-looked aspect (IPCC, 2022). The IEA has argued that energy efficiency should be the ‘first fuel’ of the energy transition due to its multiple benefits: reducing bills; minimising overall systems costs; improving energy security, health outcomes, and energy accessibility. The value of these benefits could increase with the complexity of decarbonised systems due greater renewable generation, demand electrification, digitalisation, and need for flexibility (IEA, 2015). Without improved efficiency and reduction of demand in the UK, a prohibitively expensive net zero generation system (highly dependent on yet unproven CCS technology) approximately four times larger than currently would be needed (Barrett et al., 2021). The wide ranging and multi-disciplinary nature of the benefits of energy efficiency makes their assessment much more complex than supply side technologies, to which investment decisions could be considered against (IEA, 2015). The timing of energy demand, flexibility, ramp rates, demand peaks, impact on bills per property, and ability of households and businesses to invest in measures needs to be considered in addition to annual demand. Technologies available to reduce demand can vary in energy reduction potential, capital costs (including who bears responsibility for them), and additional benefits (again-who receives them). These factors combine in consideration of cost-effectiveness, but this depends from what perspective and where the boundary of benefit is calculated from (Yushchenko and Patel, 2017). The cost-effectiveness can be extremely dependent on the technology and the siting of this boundary (i.e. which stakeholders are considered) for calculation of benefits. This influences the extent and type of policy support deemed appropriate given the ownership of costs and benefits (Molina, 2014; Rosenow and Bayer, 2016; Cho et al., 2019; Streicher et al., 2020). Comparing energy efficiency measures and policies requires methodologies which can consider the widest range of stakeholder’s perspectives and technology characteristics.

Studies have considered ranges of technologies, with a particular focus on building energy efficiency. Energy Performance Certificate (EPC) data has been used to model the cost-effectiveness and impacts of policy in Italy (Pagliaro et al., 2021), Portugal (Palma et al., 2022), UK (Ben and Steemers, 2020), Finland (Niemelä et al., 2017) and Ireland (Coyne and Denny, 2021). Heat pumps are regarded as critical to the

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decarbonisation of heating due to the their efficiency and reduction in electrical peak demand, which is for colder climates the main factor dictating peak demand (Watson et al., 2019). Modelling of UK heat pump deployment has found, that while annual heating demand with heat pumps versus gas boilers could be 8% greater, peak demand could be reduced by 8% and the maximum ramp rate by 67% depending on heating profiles, which for heat pumps there is greater flexibility (Watson et al., 2021). Heat pump deployment will be heavily influenced by policy support, such as inclusion of climate policy costs in electricity prices and direct financial incentives. The synergies between building efficiency upgrades and heat pumps are also significant (Kokoni and Leach, 2021).

Both changes to technologies and electrification of other demand sectors will lead to changes in demand for a net zero energy system. Heating and electric vehicles are anticipated to be the most important contributors to peak demand increases driven by decarbonisation, whilst minimally increasing annual energy demand in Germany and the UK (Bobmann and Staffell, 2015). Reducing the temperature effects on electric vehicle charging efficiency and increased charging infrastructure (Lindgren and Lund 2016)- in addition to increased battery size (Dixon and Bell 2020)- could help to minimise peak demand increases. For industrial demand, 79% of energy efficiency programs do not address a specific sector (Safarzadeh et al., 2020). Bottom-up modelling of industrial energy efficiency though is challenging due to the extensive heterogeneity of sectors and technologies (Fleiter et al., 2011).

Most models consider annual demand savings for individual sectors, with fewer comparing potential savings for all categories of demand. Using system demand and individual load profiles for lighting, water heating, and cooling, it was shown that the time-value of different measures can vary significantly, with notable additional reductions of CO_2 emissions (highest at peak demand), generation capacity, and distribution/transmission infrastructure (Mims et al., 2017). Analysis of hourly domestic, commercial, industrial and public demand in Brazil demonstrated that using lower temporal-resolution modelling can result in a suboptimal energy system (Pina et al., 2011). Modelling of hourly building demand for the US highlighted that time-sensitive assessment of energy savings is essential to realise the benefits of both efficiency and flexibility (Satre-Meloy and Langevin, 2019). Assessment and quantification of the multiple benefits of energy efficiency, particularly regarding overall energy system costs, can clearly be improved with higher resolution modelling. Capturing all these benefits and comparing sectoral savings potential requires a whole energy system model.

This work uses a 100%-sample categorical model to analyse the effects of energy efficiency policies on hourly electricity demand under extreme weather scenarios for electricity, heating, and transport. This allows changes in energy use and costs to be modelled for individual households and businesses. Scenarios with varying degrees of policy support are compared to command cost-effectiveness for categories of appliances, lighting, building heating, transport and industry. Three scenarios of existing and potential policies are modelled-one of the current trajectory of UK energy efficiency policy achievement, and two with increased ambitions and achievement. By projecting forward to 2045- the year of Scotland's net zero target (Scottish Parliament 2019)- the implications of these policies are quantified for changes to bills per property and peak demand. Improving understanding of the overall systems benefits contributes to assessment of energy efficiency cost-effectiveness, identified as a complex issue in the literature (Yushchenko and Patel, 2017; Rosenow and Bayer, 2016; Cho et al., 2019). The model is developed as a case study for the Scottish islands. Modelled area size is limited due to the computational intensiveness of the model. Implications of results and policy recommendations are then discussed.

2. Methodology

A model developed and validated in a previous work (Matthew and Spataru, 2023) has been used to consider the effects of specific energy efficiency policies on hourly electricity demand for domestic, commercial and industrial sectors (Section 2.1). To include private and public transport demand, the model has been expanded here (Section 2.2). The effects of demand-side energy efficiency policies have been modelled for categories of appliances, buildings, industry and transport. Three scenarios of low, medium and high demand (Section 2.3) have been compared, including a cost-benefit analysis (Section 2.4), based on historic performance of specific policies modelled forward to 2045.

2.1. *Demand model*

Hourly electricity and heating demand has been modelled using previous work validated by using recorded electricity demand for 2016 (Matthew and Spataru, 2023). It is structured around a database of every building (domestic, commercial and industrial) on the Scottish islands, for which building fabric, occupancy, appliance demand data has been assigned. A synthetic population derived from census and TUS data, is used to generate hourly categorical demand profiles which are combined with other non-domestic datasets to provide categorical demand and building occupancy profiles. Heating and lighting demand is calculated based on building occupancies, thermal characteristics and weather data with SimStock (Steadman et al., 2020), a package which automates the building energy demand modelling software EnergyPlus (U.S. Department of Energy, 2020). The effects of demand-side energy policies on hourly electricity and heating demand are modelled by varying the categories of demand shown in Fig. 1. How these are converted to model inputs is described in Section 2.3.

2.2. *Transport demand*

In addition to the domestic, commercial and industrial demand from the validated model, private and public transport demand has been added. Heavy transport modes have not been included as they are less likely to be electrified (International Energy Agency, 2022) and the main scope of this study is electricity.

As per other studies (Ramirez-Mendiola et al., 2022; Dixon and Bell, 2020), electrification of private transport demand has been included using the same TUS data which forms the basis of the domestic, commercial and industrial model. The algorithm used to model electric vehicle charging demand is shown in Fig. 2. Each 10-min timestep in the TUS data determines whether the vehicle is charging (at home-assumed to be the only charging location), producing a demand on the battery (driving) or not in use (parked away from home). The location data, reformatted to these three categories, was used with the technical data in Table 2 to apply a demand on the battery demand or a charging load (applied until the daily demand had been met). Simplistically, this method assumes that the charging demand is independent of the size of the EV battery. Using the weather data, the temperature dependency of battery charging efficiency (e.g. lower efficiency in extreme temperatures) was also considered (Lindgren and Lund, 2016). This assumes that as soon as vehicle owners return home they plug in their car to charge. This has been demonstrated to facilitate the greatest cost savings to households through increased V2G charging opportunities (Dixon et al., 2022), so should be encouraged through targeted policies.

Public transport demand has been considered as local bus demand, assumed as electric buses, rather than hydrogen. Annual local authority bus demand (BEIS, 2022b) was allocated based on bus routes. By manual scraping data from the every bus timetable on the islands, a database was created based on the number of circuits per weekday/weekend, the distance per circuit, and the start/end times (Appendix A). The total distance travelled for each bus route was then used to divide up the local authority annual demand for each island. The start/end times of buses was used to approximate when they would be charging (again assuming that when not travelling, they would be plugged in) as per Fig. 2.

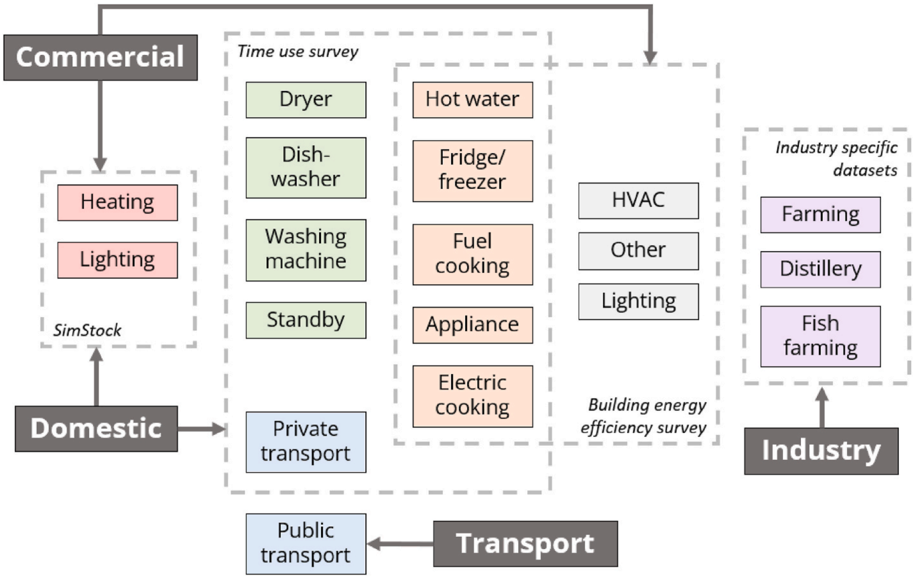

Fig. 1. Sectors and categories of demand modelled, with the main datasets (indicated in italics with the dashed boxes) described in (Matthew and Spataru, 2023), with the exception of transport which is described in Section 2.2.

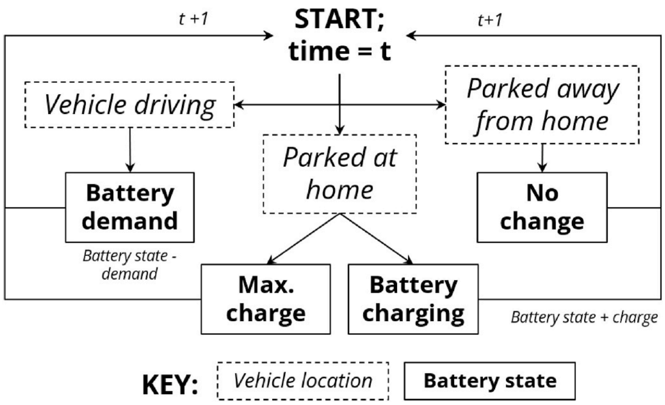

Fig. 2. Algorithm used to model electric vehicle charging profiles based on TUS locations and bus timetables.

Table 1
Technical characteristics used to model EV and bus charging profiles.

Aspect	Value	Units	Reference
Average speed [a]	38.6	km/h	(Department for Transport, 2023)
Vehicle efficiency	0.25	kWh/ km	IEA (2023)
Average battery demand per hour	9.65	kWh	Average speed x efficiency
Peak charger load	7	kW	IEA (2023)

[a] Note that there are no motorways on the islands so the average for A-roads has been used.

2.3. Modelled policies, scenarios, and weather

The energy demand and costs of policies have been modelled for appliances, buildings, heating, transport and industry. Policies have been included to highlight where national and local policy can influence overall energy demand at a variety of scales. Three scenarios of policy implementation have been modelled, which would result in High, Medium and Low final demand. The basis of the 'High' scenario is current government policy or rates of implementation, with the 'Medium' and 'Low' scenarios having improved energy efficiency potential based on setting more ambitious specific policy targets. The rationale behind the two extremes of the High and Low scenarios are described below-the Medium scenario is simply the average of the two.

High scenario-current government policies, with active policies described and historic achievement rates used to project forward to 2045. This only considers historic achievement and not stated policy targets. This includes: no change to average appliance efficiency; minimum EPC ratings for new and renovated properties of band D (average EPC of C/D by 2045); current renovation and heat pump uptake rates (58% with heat pumps by 2045); and no changes in efficiency for private vehicles, public transport or industry.

Low scenario-an improved ambition and achievement for energy efficiency with a greater subsequent reduction of demand. Rates either ensure that targets are met (such as 100% heat pump uptake or minimum EPC standards) or at a higher bound of feasible limits (such as EV efficiency). These include average appliance efficiency rating of A; renovations to a minimum EPC rating of B (the Scottish government target for the social rented sector by 2032); 100% heat pump uptake; greater private vehicle efficiency and investment in local buses; and industrial efficiency in line with industry specific net zero projections.

2.3.1. Scenarios as model inputs

The described scenarios and specific policies have been transformed into inputs to the previously described demand model. These are summarised in Table 2. For the main demand categories and aspects shown, actual policies which could influence the demand are presented. How these are considered in the model is summarised and described in more detail. Where an annual rate of change is given, it has been assumed to occur each year from now (2023) until 2045- the year of the Scottish net zero target.

These projections have been developed mainly using time use survey data (but also other behavioural datasets including heating, tourism, and business opening hours) as the basis of behaviour patterns for how energy is used in relation to specific technologies (Matthew and Spataru, 2023). Given the high resolution of the model, it has not been possible to include changes in behaviour which could be related to technology changes. The implications of this for the results are discussed in the conclusions.

2.3.1.1. Appliance inputs. To model appliance eco-design regulations,

Table 2
Summary of the modelled demand-side energy policies and the inputs used in the model for each scenario.

Category	Aspect	Representative policy	Description	Model input	Scenarios		
					High	Medium	Low
Appliances	Appliance efficiency	Appliance eco-design regulations (UK Government, 2021)	More efficient appliances are encouraged through raising ratings standards	Average appliance energy efficiency rating improves from D to:	No change	C	A
	Standby power	Appliance eco-design regulations (UK Government, 2021)	Minimum standby power per appliance is decreased	Average standby appliance demand (W):	7.7	5.5	3.5
Building fabric	New build	Building standards (DESNZ, 2023g)	New buildings added to minimum EPC rating with heat pumps	New build rate of 1.2% p.a.; minimum EPC rated:	D	C	B
	Building retrofitting	Minimum EPC targets (Scottish Government, 2022)	Buildings retrofitted to the above minimum rating- within limits of survey	Rate of annual building retrofit (%):	1%	2.2%	3.4%
Heating technology	Heating electrification	Renewable heat incentive (BEIS, 2022a); Boiler upgrade scheme (DESNZ, 2023a)	Upgrading to heat pumps assumed to occur under support schemes, remainder get direct electric heaters.	Annual heat pump uptake rate:	1%	1.8%	2.5%
Transport	Private transport demand	Internal combustion engine ban (UK Government, 2020)	All vehicles electric by 2045, improved energy efficiency for vehicles through speed limits or SUV taxes.	Average vehicle efficiencies (kWh/km):	0.3	0.23	0.15
	Public transport demand	Internal combustion engine ban (UK Government, 2020)	Increased expenditure for local bus networks	Increased number of bus routes by factor of:	1	1.5	2
Industry	Industrial demand efficiency improvements	Climate change agreements (DESNZ, 2023g)	Annual efficiency improvements for distilling and farming.	Annual energy efficiency change (%):	0%	-1%	-2%

changes in appliance energy rating were considered by assuming that the rating systems would be reclassified such that the average appliance efficiency would increase to the category given in Table 2 Using the current UK categories for appliance efficiency ratings (DESNZ, 2021), changes in the hourly demand based on the factor of improvement given in Appendix B were calculated. These factors were used to adjust the demand in the model for each different category of appliance.

Standby power was similarly reduced assuming improvements to the regulations governing the maximum power demand of devices on standby. The value used for the domestic and commercial appliance standby demand per appliance in the model was adjusted to the values given in Table 1.

2.3.1.2. *Building fabric inputs.*

The basis of the buildings model consists of a database of every building, with construction types (i.e. the thermodynamic properties of building materials) (Scottish Government, 2021a, 2021b), polygons of building shapes, and occupancy profiles assigned from the synthetic population. Combined with weather data, SimStock is used to calculate heating demand. For each scenario, building constructions has been adjusted to account for new buildings and retrofits of existing ones (in addition to the heating technology discussed below).

Building retrofits have been modelled based on the improvements listed in EPC surveys (Scottish Government, 2021b). These describe specific measures (wall/roof insulation, draughtproofing, double/triple glazing windows, heating technologies, small-scale wind/solar PV, and energy efficient lighting), as well as their property-specific costs. An improved EPC rating is assigned based on these upgrades. Modelled building improvements were only selected within the bounds of the improvements specific to each individual building as surveyed, making the scenarios considered achievable within the constraints of the existing building stock. The rate of building retrofit given in Table 1 was assumed from the range of historic rates for the region (Scottish Government, 2023).

New buildings have been added at historic construction rates in each local authority area (Scottish Government, 2023). Construction types, taken from the EPC database, have been sampled from existing buildings so that the minimum rating of new buildings matches Table 1, as per Scottish Government targets for minimum EPC ratings for various types of buildings (Scottish Government, 2022). It was assumed that all new builds would have heat pumps.

2.3.1.3. *Heating technology inputs.*

Heating technology is an input to the demand model with the technology efficiency and daily demand profile. Storage heaters use power overnight and heat pumps have profiles assigned according to archetypes of measured heating demand (Huebner et al., 2015). The High demand scenario is based on historic rates of heat pump uptake (resulting in 58% of properties having heat pumps by 2045) (DESNZ, 2023a); the Low scenario based on the annual rate of installation required for 100% of Scottish islands buildings to have heat pumps by 2045. The Medium scenario is the average of the two.

2.3.1.4. *Transport inputs.*

Transport changes have been modelled in two ways for each scenario. For domestic EVs, the efficiency of vehicles in calculating the total energy demand has been changed based on efficiency values (kWh/km) used to calculate the charging profiles (IEA, 2023). Public transport is the only aspect modelled between scenarios where the demand is assumed to increase from the Low to High scenarios. This is included by assuming that bus routes are increased by the factors given in Table 2

2.3.1.5. *Industry inputs.*

Industrial electricity demand has been assumed to improve at an annual rate, based on specific net zero modelling for the Scottish whisky industry (Ricardo Energy and Environment, 2020). More specific data was not available for the other major industries of fish processing and farming, but as whisky distilling makes up the majority of island industrial demand, the annual rates were approximated for these other sectors.

2.3.2. *Weather periods modelled*

Weather being one of major factors influencing final demand (especially as heating is electrified), the choice of weather periods will be a key factor influencing final demand. To use the results presented here for future work as input to a wider net-zero energy systems model, weather therefore needs to reflect periods of peak stress for the whole system. As dependence on intermittent renewable generation sources increases, weather patterns will dictate these periods. As the length of the modelled time period was also constrained by the available computing power (16 GB RAM, 2.6 GHz Intel i7 processor), two representative summer and winter months were modelled. These were selected from a review of UK wide adverse weather conditions for renewable generation for the two below periods characterised as the 100-year worst cases (Butcher et al., 2021). Weather data for the two months starting below was modelling using the ERA 5 reanalysis database (OikoLab, 2021).

- Winter-time wind-drought, peak demand (start date 01/12/2006);
- Summer-time wind-drought, peak-demand (start date 17/07/1986).

2.4. Cost-benefit analysis

To compare energy savings measures, capital and operational costs have been calculated where cost data was readily available (Table 3). As the demand model represents 100% of the building stock, costs have been calculated for every household and approximated based on floor space factors for commercial properties. Ranges of costs have been assumed from high-low (as per the EPC database). Implementation costs for vehicles and industrial efficiency policies have not been considered, as the heterogeneity of products and solutions specific to these sectors would make costing of these scenarios extremely complex and speculative. Additionally they are not generally considered alongside specific measures like EPC improvements or heat pumps-justification for these policies would be more likely to have a political basis than an economical one, making cost comparisons harder to justify.

Several economic metrics will be used to assess options with costings available. The levelised-cost of energy (LCOE-equation (1)) calculates the annualised cost per unit energy saved and can be compared to see if measures could be more economic to install compared with the cost of additional generation. The net present value (NPV- equation (2)) demonstrates whether an investment would have a net positive or negative value today compared with similar returns invested elsewhere. For this, a discount rate of 7.5% was used (IRENA, 2022). An internal rate of return has also been calculated-this indicates the return on investment such that the NPV is equal to zero. Measures will be assessed for a range of historic and potential domestic electricity prices-from 0.15-0.5p/kwh (DESNZ, 2023c).

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_t+O_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{Eq. 1}$$

$$NPV_r = \sum_{t=1}^{n} \frac{G-(C_t+O_t)}{(1+r)^t} \qquad \text{Eq. 2}$$

Where t = the year (from zero to n); C = CAPEX (£); O = OPEX (£); E = annual electricity saved (kWh); r = discount rate (%); n = economic life of project (years); P = cost of annual energy saved (£).

Table 3
Summary of cost data assumed.

Category	Aspect	Description	Source
Appliances	Appliance efficiency Standby power	Replacement of major appliances to specified energy rating for each household.	Appendix B
Buildings	New build	Difference in costs between new build EPC ratings equal to EPC costs.	Scottish Government (2021b)
	Building retrofitting	Cost from EPC database of costs to upgrade buildings.	
Heating	Heating electrification	Heat pump costs assumed based on floor area; storage heater from EPC.	(Kokoni and Leach, 2021; Scottish Government, 2021b)
Transport and industry	N/A	N/A	N/A

3. Results

Results are presented for both the modelled periods of extreme weather, annualised values and compared with the baseline year used for the model validation (Matthew and Spataru, 2023). Firstly, demand reduction at an hourly and annual level are presented; followed by assessment of peak demand reduction and bill savings; concluding with cost-effectiveness metrics.

3.1. Hourly demand

The range of hourly modelled demand (Fig. 3) demonstrates how the policies could affect overall demand. Comparison with the baseline year (winter average - 101 MW, summer average - 63 MW) indicates current demand (with 43% heating electrification) is analogous to the Medium scenario without generation. In this case, the improvements in energy efficiency to building stock and appliances is effectively cancelled out by the increased demand from electrification of transportation, heating, and the smaller demand of cooking for households which previously used fossil fuels. Mean winter demand without generation varies by double, from 76 to 138 MW, but less so in the summer with it ranging from 56 to 97 MW from Low to High scenarios. Most of the seasonal difference in heating (47.7%), transport (16.2%), lighting (9.3%), and industry (9.0%) is caused by temperature difference, but also changes in daylight hours (see Fig. 4).

The ratio between maximum and minimum demand provides a measure of the flexibility required in an energy system. For all scenarios without generation, this varies by a factor of 2.8-3.1 (for the whole UK it is currently 3.1) (National Grid 2023; DESNZ, 2023b). This is expected as the factors and sectors affecting maximum and minimum demand are consistent across scenarios, but with reduced energy demands through efficiency. Peak demand for the High scenario is 2.1 times greater than the Low scenario with generation (1.9 times without). Compared with peak demand of the baseline year (133 MW), High scenario peak demand increases by 47%, but decreases by 22% for the Low scenario. This change in demand should be considered against the significant increase in electrification-an additional 57% of electrically heated households and all private transport demand added from the baseline year. Energy efficiency measures could have a significant effect offsetting increasing demand through electrification, which could benefit overall system costs.

Distributed generation has a significant effect on the net demand, even becoming negative for Low scenario in the winter (17.4% of the time) and summer (7.1%). In the Low scenario, up to 30 MW could potentially be exported whilst still meeting local demand. The effect of generation on peak demand is less pronounced, but still significant, with it reducing 4.7-12.5% (noting that this occurs for the most extreme

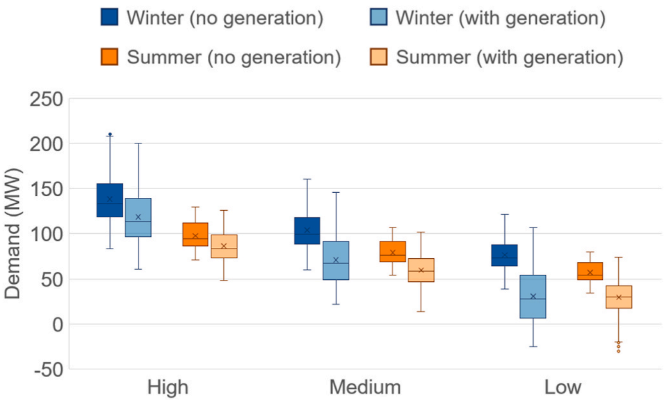

Fig. 3. Hourly modelled winter and summer demand (MW), both with and without distributed generation. The average demand in the baseline year was 63 MW in the summer and 101 MW in the winter.

generation weather conditions for the UK of low wind/high demand). However this also makes net demand much more variable, which will have other implications for technical network constraints and balancing. Increased distributed generation clearly cannot replace the need for storage and flexible demand, even at the scale (the current wind capacity of 35 MW for the High scenario up to 96 MW for the Low) potentially available to the famously windy Scottish islands.

3.2. Annual demand by sector

Under the current trajectory of energy efficiency policies in the High scenario, annual energy demand for the islands could increase by 20% (Table 4). With deployment rates sufficient to meet targets in the Low scenario and distributed generation, annual demand could decrease by as much as 65%, which would enable the islands to export electricity to the mainland more often.

By category (Fig. 4), the most significant in 2045 are private transport (34.3% of Medium scenario), heating (22.8%), and industry (22.7%). Across all categories, greater policy commitment in the Low scenario could result in decreased demand-excepting public transport, which has increased to compensate for the reduction in private transport demand. Again the huge potential reduction in demand from distributed generation is clear. For the Medium scenario, the potential for distributed generation (213 GWh) is equivalent to the demand for public transport (27 GWh), large appliances (116 GWh), and small appliances (54 GWh) combined. Industry, heating, refrigeration, hot water, and lighting have the potential to reduce annual demand from the baseline year by more than 50% in the Low scenario. Whilst changes to heating demand can also be attributed to building stock improvments, an additional value of heat pumps is that they can also reduce hot water energy demand (See Table A3).

Heating measures can be considered as building fabric upgrades (insulation, draughtproofing, glazing, etc.) and heating technology separately (direct electric or heat pumps) (Fig. 5). For building fabric only, improving the average EPC rating from D/E to B/C could reduce heating demand by 34%. For 100% heat pump deployment though (Low scenario), the reduction could be up to 64%.

Table 4
Annual demand with and without generation compared with the baseline year.

		Baseline	High	Medium	Low
With generation	Annual demand (GWh)	692.8	832.6	526.7	241.0
	Baseline change (%)	–	+20.2%	-24.0%	-65.2%
No generation	Annual demand (GWh)	692.8	958.8	740.5	541.4
	Baseline change (%)	–	+38.4%	+6.9%	21.2%

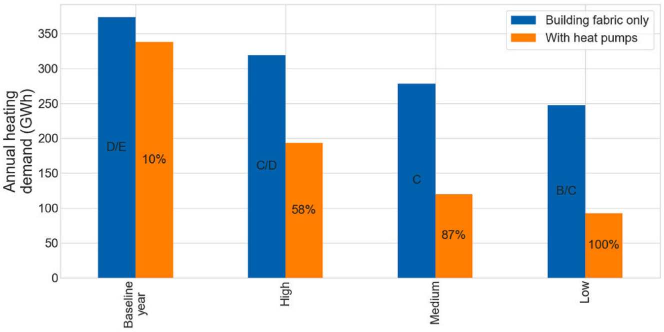

Fig. 5. Comparison of annual heating demand for building fabric and heat pumps, with average EPC rating and heat pump deployment annotated for ‘Building fabric only’ and ‘With heat pumps’ respectively. Note that heating demand for the baseline year is extrapolated from the actual 43% rate of electrification.

3.3. Peak demand

Comparing the average daily peak demand (7-10:00 and 16-19:00) with the baseline year (Fig. 6) indicates how each category could contribute to average peak demand reduction. Industry (9.1%), lighting (6.7%) and heating (5.9%) have the highest peak demand reduction potential, but large appliances (3.3%) and hot water (2.5%) are also significant. The minimal change to heating demand in the High scenario needs to be considered alongside the more than doubling of electrically heated households (from 43% in the baseline year up to 100%) and projected heat pump penetration (58.1% based on current deployment rates). Although this will not be representative of the wider UK due to much lower initial heating electrification rates, it highlights the role that heat pumps and building stock measure can have in minimising demand. The two aspects combined result in an estimated average peak demand reduction of 2.0 kW per property (domestic and non-domestic) compared to electric storage heating.

The greatest increases to demand are clearly transport, which was not included in the baseline model. This highlights the greatest potential for demand side flexibility, particularly through vehicle-to-grid (V2G) charging, which already forms a key part of UK decarbonisation plans

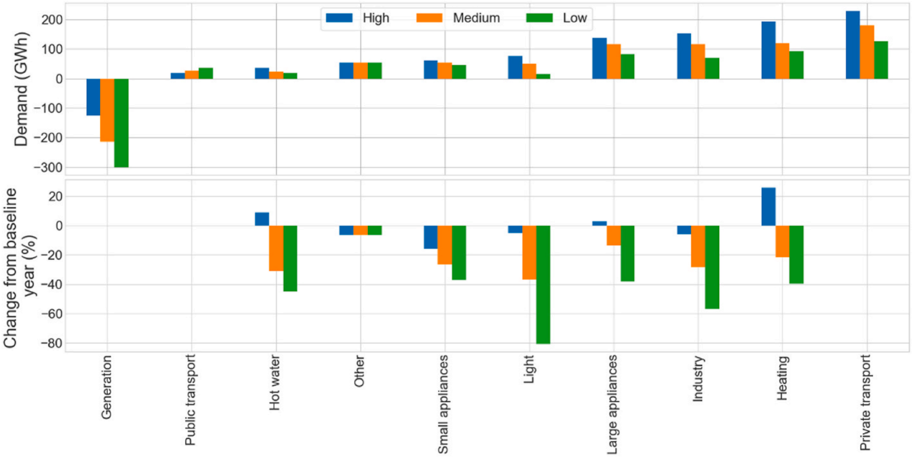

Fig. 4. Categorical annual demand and proportional change from the baseline year. Generation and transport were not modelled in the baseline year so are excluded from the lower graph. Large appliances are grouped as cooking, washing, drying, and refrigeration; small appliances are all others.

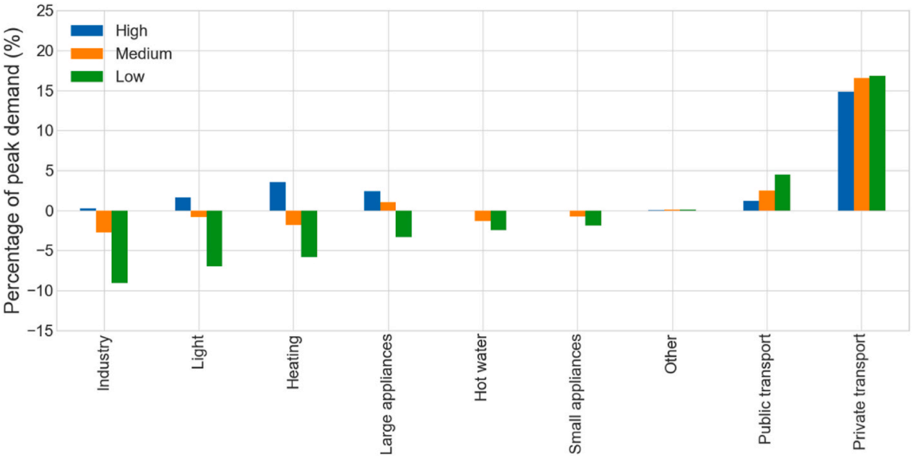

Fig. 6. Changes in average peak demand (the average demand between 7-10:00 and 16-19:00) compared to the baseline year (generation excluded due to not being included in the baseline model).

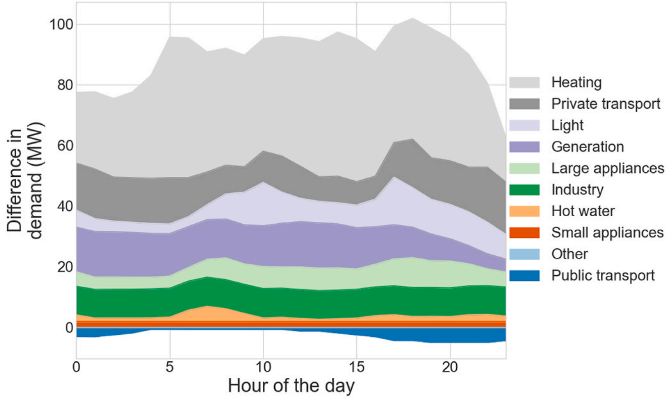

Fig. 7. Difference in demand on the modelled peak demand day between the High and Low scenarios.

(National Grid 2023). This and other sectors with the greatest peak demand reduction potential demonstrates the additional benefits of efficiency beyond annual energy (and bill) savings.

The difference between the High and Low scenarios on the peak winter demand day shows which sectors have the greatest effect (Fig. 7). Although transport has the greatest change on average (Fig. 6), heating is clearly the largest contributor on the coldest peak demand day. A distribution of recorded daily heat pump demand profiles have been assumed (Huebner et al., 2015) which will affect peak demand (particularly including demand response potential). Even if averaged over a 24-h period, heating still has the greatest contribution to peak demand. Generation again has a much lower effect on the maximum demand than annually.

3.4. *Changes to household and business electricity bills*

Looking at the highest spatial resolution of results, the individual building level, highlights the heterogeneity not apparent in the overall results. The difference in savings between the High and Low scenarios

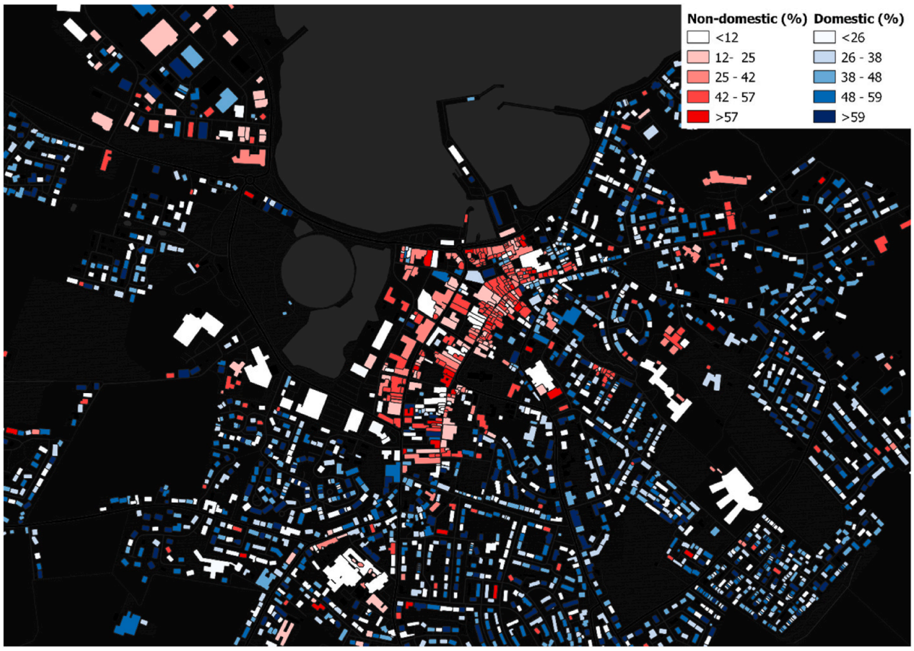

Fig. 8. Difference between the annual energy demand in the High and Low scenarios as a percentage of the High scenario for an urban area.

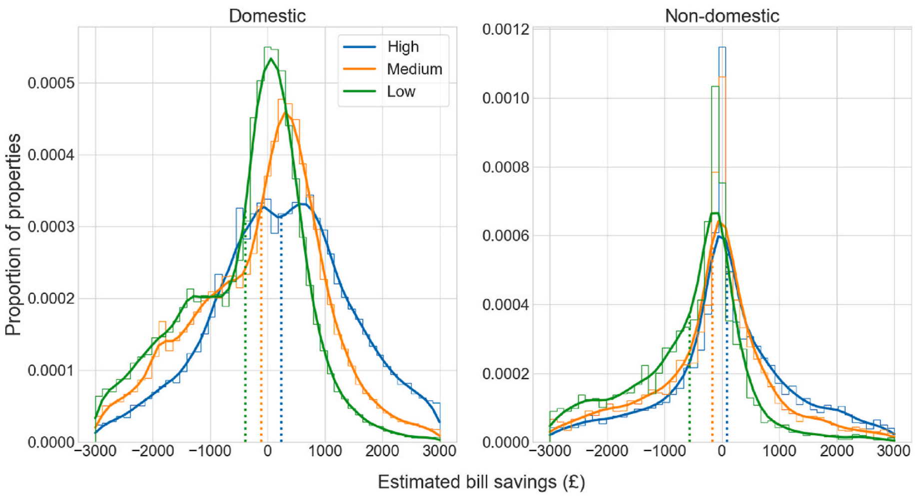

Fig. 9. Estimated annual electricity bill savings (positive for bill increase-generation is excluded) compared with the baseline year for domestic and non-domestic properties, for an electricity price of 30p/kWh. The dashed line indicates the average given in Table 5 This does not consider costs baseline year costs for transport fuel or non-electric heating.

for individual buildings (Fig. 8) shows the range of potential improvements between buildings. The potential for energy saved clearly varies significantly between households and businesses. Categorising this difference could highlight which type of buildings would be best targeted for policies-there could be a correlation with the type of business or building construction for example, but this would require further analysis.

This can also be considered in terms of the changes to electricity bills, considered only in terms of the amount of energy used (Fis. 9 generation is excluded). Including savings from heating for households which were previously non-electrically heated and transport fuel costs (not modelled for the baseline year) would result in greater reductions, but this could be offset by other operational costs-further work would be needed to assess this. The Low scenario results in much lower average bills, with average reductions of up to £559 for non-domestic properties and at about half as many properties (32% vs 57% for domestic and 21% vs 49% for non-domestic) having to pay more for electricity than they did relative to the baseline year. However, even the minimum proportion of households with increasing bills increasing (32% for the Low scenario) is significant. Successfully transitioning to a net zero energy system will require equitable policies to consider the distribution of these effects.

Considering changes to electricity bills with and without heat pumps (Table 5), there is an average difference of about £700 for the High and Medium scenarios (only heat pumps were modelled in the Low). The proportion of households with increasing bills remains less affected, due to the same number of households switching over from fossil fuels to electricity.

Table 5
Average change in bill and proportion of properties with an increased electricity bill, split by domestic/non-domestic and properties with and without a heat pump. Note that heat pump deployment is 100% in the Low scenario, so there is no direct electric heating.

	Change in bill (£)			Proportion with bill increase		
	High	Medium	Low	High	Medium	Low
Domestic	+245	-107	-381	58%	53%	42%
Non-domestic	+94	-167	-559	51%	44%	23%
With heat pump	-9	-159	-393	54%	53%	42%
Direct electric heating	+661	+468	–	66%	64%	–

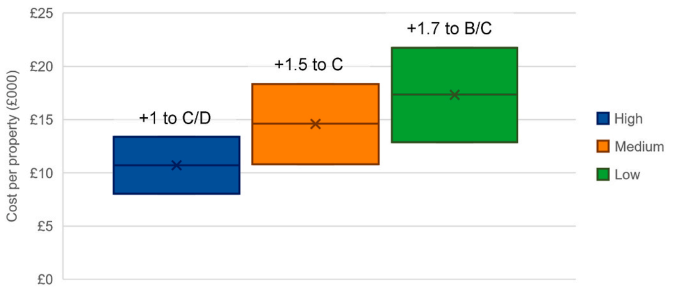

Fig. 10. Range of average cost per property to upgrade by the EPC rating indicated by the callout, with the new average EPC rating shown.

3.5. *Selected cost metrics*

The average cost per scenario (including all categories of modelled cost data) demonstrates that even for the least cost option (High scenario of current policy trajectories), the cost per property is substantial (Fig. 10). It should be noted that this cost could be spread over the years until 2045, rather than paying for all improvements at once.

Considering the levelised cost of electricity saved from the baseline year (Fig. 11), the cost-effectiveness of measures can be compared with investment in new generation. For reference, pre-2020 electricity spot prices averaged around £50/MWh, whereas post-energy crisis they have remained above £150/MWh, with peaks of more than £500/MWh (Ofgem, 2023). No measure is directly cost-competitive with pre-energy crisis electricity prices. Compared with post-crisis electricity prices, only

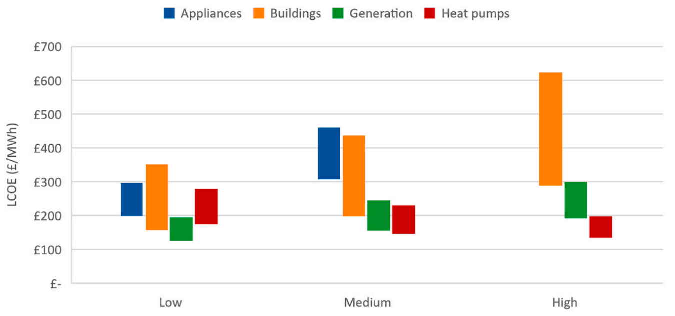

Fig. 11. 11Range of LCOE in the EPC database or appliance database. Appliance costs for the High scenario >£1000/MWh have been removed.

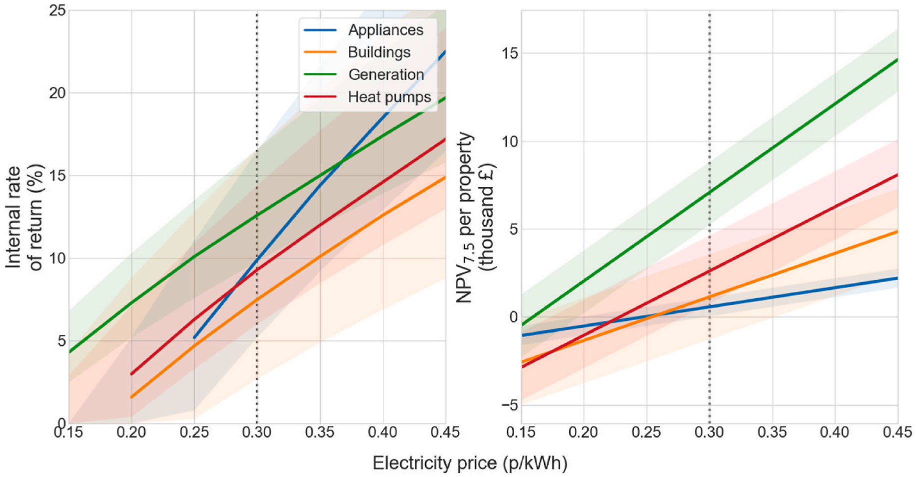

Fig. 12. 12Payback period (left) and the $\text{NPV}_{7.5}$ (right) for specified measures over a range of electricity prices for the Medium scenario. Current approximate electricity prices (30p/kWh) by dotted lines.

heat pumps (compared with electric storage heaters) and building fabric upgrades (at the lower end of price ranges) are competitive. It should be noted that heat pump LCOE decreases from the Low to High scenario due to being tied with the changes in building fabric between scenarios (the High scenario having lower building efficiency means more energy is saved). Appliance are the only modelled aspect which entirely exceed electricity prices, indicating that other measures could more cost effective to target purely from an energy saving perspective (see Fig. 12).

3.6. Conclusion and policy implications

This has study assessed the effects of energy efficiency policies using a 100%-sample electricity heating and demand model, validated using recorded demand data (Matthew and Spataru, 2023) and expanded to include public and private transport. Policy categories of appliances, building fabric, heating electrification, transport, and industry are all considered. Three scenarios of High (the UKs current policy rate of implementation, not the targets), Low (achievement of stated targets), and Medium (average of the two). Results have been compared to the baseline validation year of the model to quantify changes in demand.

The model has been set up such that only technologies changes from the baseline year affect the projected electrified demand. As such, it is not able to capture some of the complex interactions between technology, efficiency, and behaviour. The "rebound effect"- where expected energy savings through more efficient technologies are less than expected due to increased usage-varies between sectors and technology types. This has been estimated at an economy wide level as up to 10% for transport and up to 30% for heating (UKERC, 2007). For heating, the model is calibrated so that changes to EPC rating reflect recorded differences (Few et al., 2022), but technology changes like heat pumps could also affect primary heating demand through changes in demand patterns (Terry and Galvin, 2023). For other demand sectors, this could include having a greater number of appliances or driving further in a more fuel efficiency vehicle. Other behavioural changes, particularly from non-energy policy specific effects (Royston et al., 2018), are also not accounted for but could have a significant effect on either increasing or decreasing demand. Results presented here are therefore likely representative of an upper bound of potential savings.

From now till Scotland's 2045 net zero target, the three scenarios correspond to an annual demand change of +0.6%, -1.3%, -3.2% for the High, Medium and Low scenarios respectively. For context, the IEA's net zero pathways recommends efficiency improvements of 4% annually (IEA, 2022). The trajectory of current demand-side policies (High scenario) would likely result in an average electricity demand increasing by 21% and peak demand increasing by 58%. The electrification of other demands (heating and transport) would negate reductions in industry, appliances, and lighting. As nearly half of all properties on the islands are currently electrically heated, the increase would be more significant for the rest of the UK, which is reliant on gas for heating. Specifically for the islands, with already constrained local grids (Orkney Renewable Energy Forum, 2014), but also to a lesser extent the whole UK, the capacity of existing infrastructure for increased electricity transmission is limited (DESNZ, 2023e). Failure to invest in energy efficiency will require increased spending on other options such as grid upgrades or distributed storage. Understanding the trade-offs in for this requires whole energy systems modelling. However, given the potential benefits modelled here, such as reduced electricity bills- but also others such as improved health outcomes and air quality (IEA 2015)- surely efficiency should be the first preference.

The peak demand increase of 2.3 between the baseline year (excluding heating) and the High scenario is consistent with other estimates of 1.5-2.9 (National Grid 2023; Bobmann and Staffell, 2015; Watson et al., 2019). Heating (35.3-39.1% of peak demand by scenario) and electric vehicle charging (25.1-39.9%) are the two factors which contribute most to peak demand. Efficiency improvements just for these two sectors could reduce this by 33% from the High scenario. This model has assumed a range of standard heating profiles for heat pumps (Huebner et al., 2015) and overnight for storage heaters (Matthew and Spataru 2023)- however further reductions should be possible with digitised and smarter charging/heating profiles. This could only be enabled in conjunction with building fabric upgrades given the low EPC rating of current building stock. The significant increase in demand from electric vehicle charging (23.2-24.4% of annual and 20.7-22.7% of peak demand) highlights how critical it will be for grid stability and reducing reliance on peaking generation. The calculated peak demand increases could be much lower through improved flexibility of EV charging, domestic batteries (particularly combined with generation), or heating. Policies to incentivise smarter EV charging and other flexibility will be crucial to benefit electricity networks.

Heat pumps are the most important technology modelled due to reducing both annual and peak demand which is the main driver of overall system size and cost. Compared with direct electric heating, the model estimates savings of 2.0 kW annual peak demand per property. Scaled up to the 28 million UK households could make a national difference in peak demand of 56 GW. Considering model uncertainty though (such as type of building stock or heating behaviour changing with heat pumps), even half of this would be significant. Heat pumps also have the potential to reduce energy demand for hot water through increased efficiency. Modelling of the current rate of heat pump installation though highlights that targets will not be met under the achievement of current policies, with only 58% of households having them under the High scenario. While the Governments recent upgrading of the heat pump grants available to households by 50% to £7500 (DESNZ, 2023d) is laudable, it remains to be seen whether or not this will inspire enough confidence in a heat pump market, particularly given simultaneous commitment to trialling hydrogen for domestic heating (DESNZ, 2023f). The modelled changes to electricity bills highlights (Figs. 8 and 9) that businesses could be subject to the same unequal distribution of costs to decarbonise as households, but with the closure of the renewable heat incentive, similar support mechanisms may be needed for the non-domestic sector.

Maximising the benefits of heat pumps requires upgrading building fabric. Modelled annual demand shows heat pumps could reduce heating demand by 2.6 times, but this would be increased to 4.0 times when combined with building fabric. Interactions between heat pumps and building fabric upgrades are captured in the model via the air change rate, a variable defined in EnergyPlus which can be used calibrate models (Calama-González et al., 2021), meaning that inefficient use of heat pumps in poorly insulated homes is considered. Improved building efficiency not only reduces demand-improved heat retention of buildings also facilitates heat pumps to run continuously or shift peak demand. This is not to mention the additional health benefits for warmer, better insulated homes (Citizens Advice, 2023), which would be especially significant for the islands with some of the highest fuel poverty rates in the UK (Orkney Island Council, 2017). Wider ranging measures will be needed, such as the forthcoming Future Homes Standard, with anticipated upgrades to minimum building efficiency requirements. Ambitious energy efficiency targets in building standards could be doubly beneficial as measures designed into new buildings could be cheaper than later retrofitting.

By sector, industrial demand electricity demand (13.0-15.9% of the total) is only third to EVs (23.2-24.3%) and heating (16.1-20.1%). It has the greatest average peak demand potential reduction (although not absolute peak, which is mainly heating demand) and second highest percentage reduction of modelled categories. These results are however based on the simplification of assuming that improvements modelled for net zero whisky industry pathways (Ricardo Energy and Environment, 2020) would be relevant to farm, fish farming, and fish processing. Due to lack of data, industrial demand was approximated from a range of annual sources for electricity only, which means that it also does not consider the increased electrification of other demand types, which would likely more than offset the projected savings for the heat-intensive distilling industry. The model and accuracy of the industrial potential would be greatly improved with an industrial model more decomposed into constituent energy demands, but the heterogeneity of industrial demand continues to make this complex (Fleiter et al., 2011). Better understanding of the specific efficiency and wider decarbonisation options for different industries would help to inform what scope for efficiency improvements each has and so how policies are designed to support them. Policies can also be targeted at specific industries, such as with efficiency auctions in Switzerland (Regulatory Assistance Project, 2022).

Results, including the proportion of households that could experience an increase in electricity bills (42–58%) and the total cost of modelled efficiency upgrades (£8-22k per building), highlight the importance of a “just transition”, which can be enabled through energy policy. It can be defined as ensuring that no household or business is unfairly burdened in the transition to net zero. Results showed how household electricity bills could fall on average (except for the High scenario), but even at the best-case Low scenario, 42% of properties could have a higher bill-mainly due to additional heating and vehicle electrification. Meeting the Scottish Government target on the islands for the social rented sector of EPC B could cost up to £22,000 per household (likely more for the least efficient buildings). This, combined with the potentially positive NPV of all measures under current electricity prices, highlights that without financial policy support, efficiency improvements and access to their benefits will only be affordable for the well-off (Kokoni and Leach, 2021). Supporting those less able to afford efficiency upgrades should play a key role in efficiency policy, with greater efficiency enabling whole system benefits such as peak demand reduction.

The modelled distributed generation (mostly wind, but also solar PV) could reduce annual demand by up to 55.5%, but other benefits were less significant. Even during the worst case month of wind-drought for the whole UK, energy could be exported 17% of the time. Although local weather at the extremities of the UK might not correspond with the UK-wide worst-case, any reduction in network demand would be beneficial at periods of acute stress for energy systems dominated by intermittent renewables. Geographic diversity of supply can benefit grid balancing, stability, and consistency of supply from renewables (Matthew and Spataru, 2021). Whilst the capacities included are considerable (up to 90 MW in the Low scenario, compared with peak demand of 107 MW), generation modelled for Orkney (17.2 MW) is actually lower than the currently installed FiT capacity (19 MW) (Department of Buisness Energy and Industrial Straegy, 2020). Local government and planning approvals will play a significant role in approving distributed generation which the overall energy system could benefit from. Whilst this assessment does not consider technical grid constraints, the maximum ramp rate increase of 2.8 MW with generation would be manageable-as it already is on Orkney.

Further work will be required to integrate the demand model with a wider supply and transmission one to better understand the implications for the electricity system. This would highlight the trade-off between efficiency and infrastructure upgrades, in addition to the modelled benefits of peak demand reduction (the most important factor dictating overall energy system size and cost) and bill savings-not to mention health benefits not modelled here. This could make investment in efficiency more attractive than increasing generation and transmission capacity. An ostensible factor in the UK government’s rejection of a target for onshore wind is the impact on local communities and landscapes, but without sufficient reduction in electricity demand, network upgrades could contribute to exactly the same roadblock (Thomas, 2023). While this model has attempted to demonstrate the potential to simultaneously assess the multiple benefits of energy efficiency measures, only with consideration of the impacts on the whole system can these be fully assessed.

Improved frameworks for quantifying the multiple benefits of energy efficiency could help to inform policy makers. Whilst energy saved is the simplest to calculate, it does not capture the additional benefits of peak demand, reduced bills, improved health outcomes, minimised energy system size or emissions reductions. Simplistically, the energy systems transitions needed to reach net zero can involve investment in supply and/or demand side measures. Whilst both will be needed, the onus in the UK policy has been on the supply side. Failure to invest in demand reduction will necessitate increased spending on network, balancing, storage, and generation. Failing to meet interim targets will make later ones more difficult, and could eventually jeopardise achieving net zero entirely. For example, failure to install 600,000 heat pumps annually by 2028 could require a much larger generation system, making electricity decarbonisation by 2035 much harder (not to mention stressing supply chains in a later rush to over-compensate) (DESNZ, 2023g). The presented framework to assess the multiple additional benefits of energy efficiency could help to redress this by quantifying the most important benefits that energy efficiency could provide. In the short six months that it lasted, the Governments Energy Efficiency Taskforce met just four times before being shut down in September (UK Government, 2023). Given the potential reductions in overall systems costs, transmission infrastructure improvements, generation capacity, bill savings, and achievability of net zero: why is efficiency not being treated as an integral part of net zero plans?

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CRediT authorship contribution statement

Chris Matthew: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Chris Matthew reports financial support was provided by Engineering and Physical Sciences Research Council.

Data availability

The data that has been used is confidential.

Appendix A

Island	Bus number	Number of laps			Dist. per lap	Total dist.	Reference
		Week-day	Satur-day	Sun-day			
Mainland of Orkney	6	7	7	3	25	1125	(Orkney Islands Council, 2023)
	2	6	6	3	15	585	
	3	7	3	0	20	760	
	x1	30	20	10	25	4500	
	4	30	20	10	10	1800	
	7	3	3	0	70	1260	
	8s	1	1	0	70	420	
	9	11	11	4	20	1400	
Mainland of Shetland	4	23	25	7	20	2940	ZetTrans (2023)
	6	32	18	9	30	5610	
	8	2	2	0	40	480	
	9	10	10	11	30	2130	
	12	5	0	0	25	625	
	19	6	6	0	40	1440	
	21	6	6	0	60	2160	
	23	13	11	0	40	3040	
	24	2	2	0	150	1800	
	24y	8	7	0	40	1880	
	28	8	6	0	30	1380	
	29	7	7	0	20	840	
	30	9	6	0	30	1530	
Lewis and Harris	w1	5	4	0	40	1160	(Comhairle nan Eilean Siar, 2023)
	w2	7	7	0	70	2940	
	w3	4	4	0	40	960	
	w4	9	4	0	60	2940	
	w5	17	17	0	15	1530	
	w6a	16	16	0	25	2400	
	w7	9	0	0	15	675	
	w8	9	5	0	30	1500	
	w9	7	7	0	50	2100	
	w10	7	7	0	50	2100	
	w11	3	2	0	50	850	
	w12	2	2	0	50	600	
	w13	9	2	0	30	1410	
Benbecula	w14	3	4	0	15	285	
	w16	8	5	0	40	1800	
	w17	9	6	0	40	2040	
	w18	8	7	0	90	4230	
	w19	5	2	0	20	540	
Barra	w32	5	5	0	20	600	
Skye	54	3	0	0	40	600	Stagecoach (2023)
	52	5	3	0	60	1680	
	55	9	0	0	35	1575	
	56	14	4	0	40	2960	
	57	11	7	0	80	4960	
	152	3	0	0	60	900	
	150	3	0	0	30	450	
	155	5	0	0	40	1000	
Islay	450	10	7	0	50	2850	Argyll and Bute Council (2023)
Jura	451	9	6	0	40	2040	
Mull	96	3	3	2	60	1200	
Arran	322	15	10	0	20	1700	(Visit Arran, 2023)
	323	15	10	0	20	1700	
	324	15	10	0	20	1700	

Appendix B

Table A1
Changes to appliance energy efficiency ratings based on categories for each type of appliance (DESNZ, 2021)

Appliance	A	B	C	D
Lighting	56%	37%	19%	0%
Refrigeration	49%	36%	20%	0%
Washing machine	35%	25%	14%	0%
Oven	58%	42%	23%	0%
Dishwasher	36%	24%	12%	0%

Table A2
Costs to replace major appliances by energy efficiency rating sampled from a cost comparison website (TurnRound, 2023).

Cost (£)	A	C	D
Washing machine	355	289	259
Dryer	389	269	229
Fridge	600	500	350
Oven	370	250	200
Dishwasher	985	688	549
Total	2699	1996	1587

Table A3
Assumed lifetime of energy efficiency measures used for cost-effectiveness calculations (Hoffman et al., 2015).

Aspect	Lifetime
Appliance efficiency	8
Standby power	8
Demand side response/P2P trading	15
New build	15
Building retrofitting	15
Heating electrification	15
Private transport demand	15
Public transport demand	15
Industrial demand efficiency improvements	15

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