4D Heat

Using domestic heat to address wind constraints

A Network Innovation Allowance project joint funded by National Grid ESO and Scottish & Southern Electricity Networks

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Everoze is an employee-owned consultancy, specialising in renewables, storage and wider energy flexibility. Our unique strength is bridging the gap between the technical and the commercial. We exist to help our clients accelerate the transition to a decarbonised energy system. We're a team of consultants who are flexible, experienced and interdisciplinary, based in Europe and active globally. We are a trusted advisor to some of the biggest brands in the sector, supporting them to make projects, companies and technologies futureproof and financeable.

PassivSystems have developed a range of home energy services which are changing the landscape of the energy industry. We are a pioneering company at the forefront of making energy use more efficient and more affordable for millions of households. Our motivation is to help consumers, asset owners and businesses get better value for money and to make a significant difference to global emissions.

1. Executive summary

In the year 2030, up to 9% of constrained wind, equivalent to 540GWh/year, could be absorbed by domestic off-gas grid electric heating across Scotland by exploiting the flexibility in heating. This delivers a £24m/year saving in wind constraint payments and a further £2m/year in environmental and societal benefits, providing a net benefit to the system and consumers.

National Grid ESO currently experiences considerable constraint issues on the transmission network, whereby the electricity system is unable to transmit power to the location of demand, due to congestion at one or more parts of the network. It is often cheaper to constrain generation (typically wind) rather than build new grid infrastructure. At present, constraints currently cost the ESO around £500m per year.

The 4D Heat project adopts a whole system view, exploring how constrained wind might be otherwise put to meaningful use in the system. We address the question: *"what is the maximum volume of wind energy that the ESO could avoid having to curtail, by incentivising electric residential heating turn-up and flexibility at times of constraint?"* Importantly, this is subject to not increasing the cost to the ESO, DSO or end-consumer.

4D Heat therefore explores the ability of heat flexibility to absorb wind that would otherwise have been curtailed due to England-Scotland (B6) transmission constraints and the key drivers for achieving this. This is done by analysing an off-gas grid area in Skye and extrapolating to off-gas grid Scotland, assuming no other constraints in the Scottish network. In addition to considering the transmission system, another requirement is that the flexibility solutions do not cause additional constraints on the distribution network.

Scenarios for 2020 and 2030 are examined with different heating system types, control systems, and direct and indirect price incentives for customers.

The analysis demonstrates that a reduction in curtailed wind of up to 17% (222 GWh) in 2020 and 9% (540 GWh) in 2030 is achievable. This corresponds to CO_2 savings of up to 42Gt in 2020 and 26Gt in 2030 – the main contributing factor to the £2m of environmental and societal benefits delivered. Overall system-wide cost reductions in the region of £48m per year by 2030 are achievable (see Figure 1), with some households saving up to 18% on their annual energy bill.

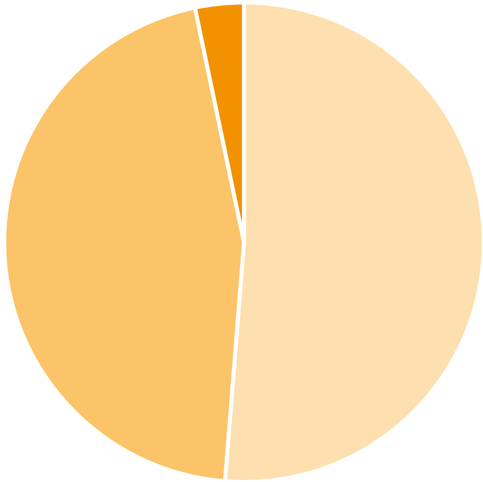

Figure 1: The breakdown of system-wide benefits from implementation of smart controls combined with dynamic time of use tariffs and direct wind curtailment incentives per annum in 2030

The total amount of constrained wind which can be absorbed is limited by the size of the off-gas grid electric heating load and the need to maintain customer comfort. Therefore whilst electric heating flexibility is one option to reduce wind constraints, with the associated cost and CO_2 benefits, other measures will be required if further reductions are to be achieved.

The scenario analysis identified three ways for the ESO and DSO and energy consumers to reap benefits at no additional cost in accessing heat flexibility to manage curtailed wind:

- **Smart controls** which optimise heating systems. These provide the means to control the heating devices and optimise supply, delivering financial benefits to households in their own right. They provide an overall payback across customers and the system of around 7 years.

- **Time of use tariffs.** Future market-led dynamic time of use tariffs available in the retail market could provide the strongest signal for households to modify their heating loads in response to the grid supply mix. They indirectly incentivise the use of curtailed wind due to periods of high wind generation (and therefore constraints) generally having a strong correlation with low wholesale power price periods. Switching to time of use tariffs (with smart controls) has the ability to reduce household bills by up 12%. The overall payback across customers and the system could be as low as 1.5 years.

- **Direct wind curtailment incentives**. Such incentives have the ability to increase the curtailed wind absorbed by a further 40-80% compared to using a dynamic time of use tariff alone, while still providing additional savings to the ESO and households. Smart controls are crucial in unlocking this value stream in a way that is acceptable to occupants. The overall payback across customers and the system is around 1 year when using smart control, time of use tariffs, and direct incentives to directly drive consumption of otherwise curtailed wind.

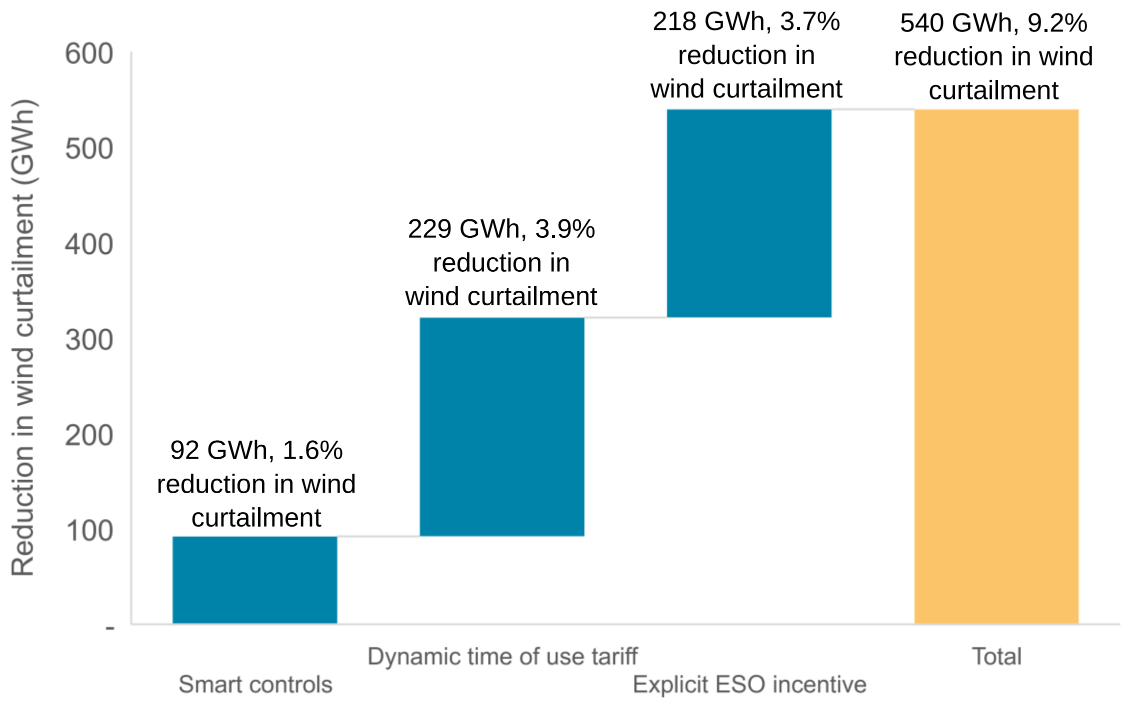

Figure 2: Reduction in wind curtailment in 2030, with all three measures implemented.

The research leads to six clear recommendations:

1. **Be a proactive voice on energy supply market reform:** The ESO and DSO have a case to promote innovation in the energy supply market – for instance via mandatory half-hourly settlement, or supporting the development and addressing barriers to energy-as-service propositions.
2. **Support the evidence base for smart controls:** It is in the interest of ESO and DSO that mandatory smart controls are part of any policy incentive for low carbon heat. Promote this requirement to BEIS and Ofgem as part of the engagement process for incentives designed to encourage the installation of new low carbon heating systems.
3. **Adopt a 'market enabling' role for industry innovation:** Engage with and support the wind industry and innovators to explore more innovative

energy market mechanisms to include residential demand side flexibility. Innovative new PPA's which incentivise localised heat turn up services would drive customer "pull" for access to such services.

4. **Continue ESO and DSO service reform**. Improve accessibility to data to ensure that flexibility providers have long-term visibility of the location of future network needs, and trial empirical demonstrations to identify additional real-life barriers which may be difficult to identify or understand from a desk-based review.

5. **Consider implications for DSO Business Plans:** Explore whether DSOs' *Vulnerable Customer* strategies might help make fuel-poor homes heat-flexibility ready.

6. **Conduct further modelling:** Develop models which adopt a whole-home approach, which incorporate empirical data, and test the impact of household diversity. In addition, conduct analysis of sub regional constraint issues.

Most importantly, the findings of this project demonstrate the need for **whole system thinking in the broadest sense**, where the ESO and DSO are compelled to more proactively engage with wider energy market reform and innovation in end user propositions.

1. Introduction

This project aims to quantify the maximum volume of wind energy (MWh) that could cost-effectively avoid being curtailed, by controlling electric residential heating in off-gas grid Scotland.

1.1. The problem

The ESO currently experiences considerable constraint issues on the transmission network, much of which is due to the generation of renewable energy. These constraint issues arise predominantly due to an abundance of onshore wind power, 8.4GW of which is installed in Scotland (89% of total wind capacity in Scotland)[1], and limited transmission network capacity to move this power down to England and Wales where the predominant loads are located. ESO constraint costs are currently over £500m/annum[2] and are expected to increase if the wind capacity grows as currently forecasted.

1.2. A potential solution

The demand side flexibility offered by residential electric heating has the potential to partly mitigate these constraints. The 4D Heat project explored whether time-shifting electrified residential heating in off-gas grid Scotland can be used to reduce wind curtailment, without adversely impacting the distribution network and without costing the ESO, DSO or end-consumer more.

In addition to reducing ESO constraint costs, 4D Heat promises CO_2 savings and possible further societal benefits, whilst ensuring that distribution network thermal limits are not exceeded. These are to be realised by reducing the volume of zero-carbon renewable generation that is curtailed and potentially mitigating associated fossil generation that would be turned up south of the Scottish border.

1.3. Project objectives

The core question underpinning 4D Heat is this: “what is the maximum volume of wind energy that the ESO could avoid having to curtail, by incentivising electric residential heating turn up at times of wind curtailment?” Importantly, this is subject to not costing the ESO, DSO or end-consumer more.

To answer this question, the 4D Heat project had three primary objectives:

- Analyse how well DSO and ESO constraints match with the available flexibility from electric heating loads,

[1] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables
[2] https://www.nationalgrideso.com/balancing-data/system-balancing-reports

- Conduct a cost benefit analysis (CBA) to identify if a domestic turn-up service is a cost effective and scalable solution, and
- Evaluate consumer perspectives and potential routes to market.

1.4. Project scope

The 4D Heat project focused on the role that off-gas grid residential space heating and hot water loads in Scotland could play in reducing wind curtailment. Other technologies such as electric vehicles and home batteries were out of scope for this analysis. The Isle of Skye was selected as a representative off-gas grid area in the north of Scotland, within the Scottish and Southern Electricity Networks (SSEN)license area, to be studied in detail. The results for Skye were then linearly scaled up to reflect the heating loads of all off-gas grid homes in Scotland.

1.5. Project methodology

The 4D Heat project utilised desk-based study techniques. Technical modelling was used to match the available flexibility from domestic electric heating with transmission network constraints.

Techno-economic modelling was used to assess the benefits of using the flexibility of residential heating to manage constraints, compared to the traditional solution of curtailing renewable generation.

Desk-based research was used to assess existing consumer perspectives on the potential use of residential heating to provide flexibility services. In addition, existing and novel route-to-market business models were qualitatively analysed.

1.6. Project scale and outputs

The 4D Heat project spanned 6 months and as a whole system project, entailed collaboration of 5 project partners, who together span a range of industry perspectives. These partners were: (1) Delta-EE (lead partner), (2) Everoze, (3) PassivSystems, (4) National Grid ESO, and (5) SSEN.

The partners produced the following outputs:

- Quantification of the scale and cost effectiveness of flexibility from residential electric heating to help solve both ESO and DSO constraints;
- Conclusions for Scotland and beyond on how residential heat can be used to address both ESO and DSO constraints;
- Recommendations to realise the potential in practice.

2. Methodology overview

Scenario-based modelling was used to quantify the total volume of curtailed wind that could be absorbed without adverse impacts on the distribution grid or home comfort. A system-wide cost benefit analysis was also conducted.

2.1. Scenarios investigated

The modelling was based on scenarios that isolate the differing effects of:

- Home hardware (driven by policy): Installing smart controls;
- ESO markets (driven by ESO): Directly driving wind consumption by offering homes a financial incentive to increase demand at times of curtailment – explicit wind consumption incentivised; and
- Energy supply market (driven by regulation): Adopting dynamic time of use tariffs (ToU), which reflect the wholesale electricity price plus variable Distribution Use of System (DUoS) charges.

Furthermore, two different base modelling years, 2020 and 2030, allowed for the changes expected in the wind generation capacity and housing stock to be investigated. The 2030 modelling assumes that the predicted increase in onshore wind generation in Scotland in the FES Two Degrees scenario has occurred, leading to higher levels of network constraint. By 2030, improved insulation levels and an increase in heat electrification are anticipated, alongside the removal of the RTS[3] scheme. Table 1 provides an overview of all the different scenarios investigated.

The 2020 scenarios are based on the current building stock representing a present-day business as usual base case. The scenario where smart controls are fitted allowed for the benefits of smart controls to be isolated from any impacts resulting from explicit incentivisation of wind consumption. In the core 2020 scenarios it was assumed that RTS homes were not able to be fitted with smart controls. A parallel set of scenarios investigated the effects of switching as many of the RTS homes as possible (without overloading the distribution grid) onto Economy 7[4] (E7). It was assumed that these now converted homes could be fitted with smart controls and further incentivised to used wind.

[3] Radio Teleswitch Service (RTS) is a type of household electricity meter system with an inbuilt remote-control mechanism. It uses BBC long-wave radio signals to allow scheduling of storage heaters and water heating to avoid distribution network constraints. According to the ENA (2016 Consultation on Radio Teleswitch Broadcasting Provision) there are over 1.6 million RTS meters in operation across GB. The RTS is set to be decommissioned by 31st of March 2023.
[4] This is a static time of use tariff with an off-peak 'cheap rate' period between 0am – 7am and a 'peak rate' tariff the rest of the day.

A key difference between the 2020 and 2030 scenarios is that the building stock in 2030 has been assumed to change – with more homes fitted with heat pumps and improved insulation. The 2030 base case scenario assumes that all homes with storage heaters are on an E7 tariff (due to phase out of RTS) and heat pump homes are on a flat tariff. As with the 2020 base case scenarios, the benefits of adding smart controls alone and then further explicitly incentivising wind consumption was investigated. Two of the 2030 scenarios investigate the effects of having all homes on a ToU tariff (with smart controls) and then further explicitly incentivising wind consumption.

Table 1: Modelling scenarios investigated

Scenario	Building stock & wind curtailment profile		RTS homes present	Main electric heating technology	Smart controls installed	Explicit wind consumption incentivised	Dynamic ToU tariffs used
	2020	2030					
A1: 2020 Base case	✔		✔	Storage heaters			
B1: Smart controls only (RTS)	✔		✔	Storage heaters	✔		
C1: Optimisation to ESO wind constraints (RTS)	✔		✔	Storage heaters	✔	✔	
B2: Smart controls only	✔			Storage heaters	✔		
C2: Optimisation to ESO wind constraints	✔			Storage heaters	✔	✔	
D: 2030 Base case		✔		Heat pumps			
E: Smart controls only		✔		Heat pumps	✔		
F: Dynamic ToU tariff		✔		Heat pumps	✔		✔
G: Optimisation to ESO wind constraints		✔		Heat pumps	✔	✔	
H: Dynamic ToU tariff + Optimisation to ESO wind constraints		✔		Heat pumps	✔	✔	✔

2.2. Overall modelling approach

The electricity use for domestic space and hot water heating for a representative off-gas grid region of Scotland was modelled, including modelling the consumption of 3,589 individual homes. These modelling outputs were then used to estimate the system cost reduction that could be achieved from absorption of curtailed wind through matching wind curtailment with domestic heating flexibility for various scenarios in 2020 and 2030.

The challenge was to develop a model architecture which joined up a macro and micro lens – to both fairly represent micro heating behaviour in multiple home archetypes, whilst drawing out macro implications for Scotland. The overall model architecture is shown in Figure 4 . The key inputs defined were:

- Housing stock (shown in dark blue)
- Household heating system (green)
- Distribution system (purple)

Notable limitations of the modelling approach include:

- **Perfect foresight:** It is assumed that at the start of each day a perfect forecast for the next 24 hours is available for individual household energy demand, energy tariff prices and quantity of curtailed wind.
- **Single day focus:** Any impact of wind-optimisation on the subsequent energy demand beyond 24 hours after the optimised day has ended has not been considered.
- **Representative archetypes and area:** The analysis relies on modelled baseline and wind-optimised energy demand profiles for space heating and hot water for each home archetype being representative of actual energy use. The analysis also relies on feeder archetypes being representative of the network on Skye – and ultimately off-gas-grid Scotland.
- **Pricing:** The modelling assumes a curtailed wind use tariff discount set at a constant value of 4.494p/kWh for both 2020 and 2030.
- **No transmission constraints within Scotland:** When scaling up the results from Skye to all off-gas grid Scotland it is assumed that this can be done without causing any additional transmission system constraints at other constraint boundaries (e.g. B1 and B4). The focus is therefore on the Scotland-England constraint boundary (B6) alone and no sub-regional power flow analysis was carried out.

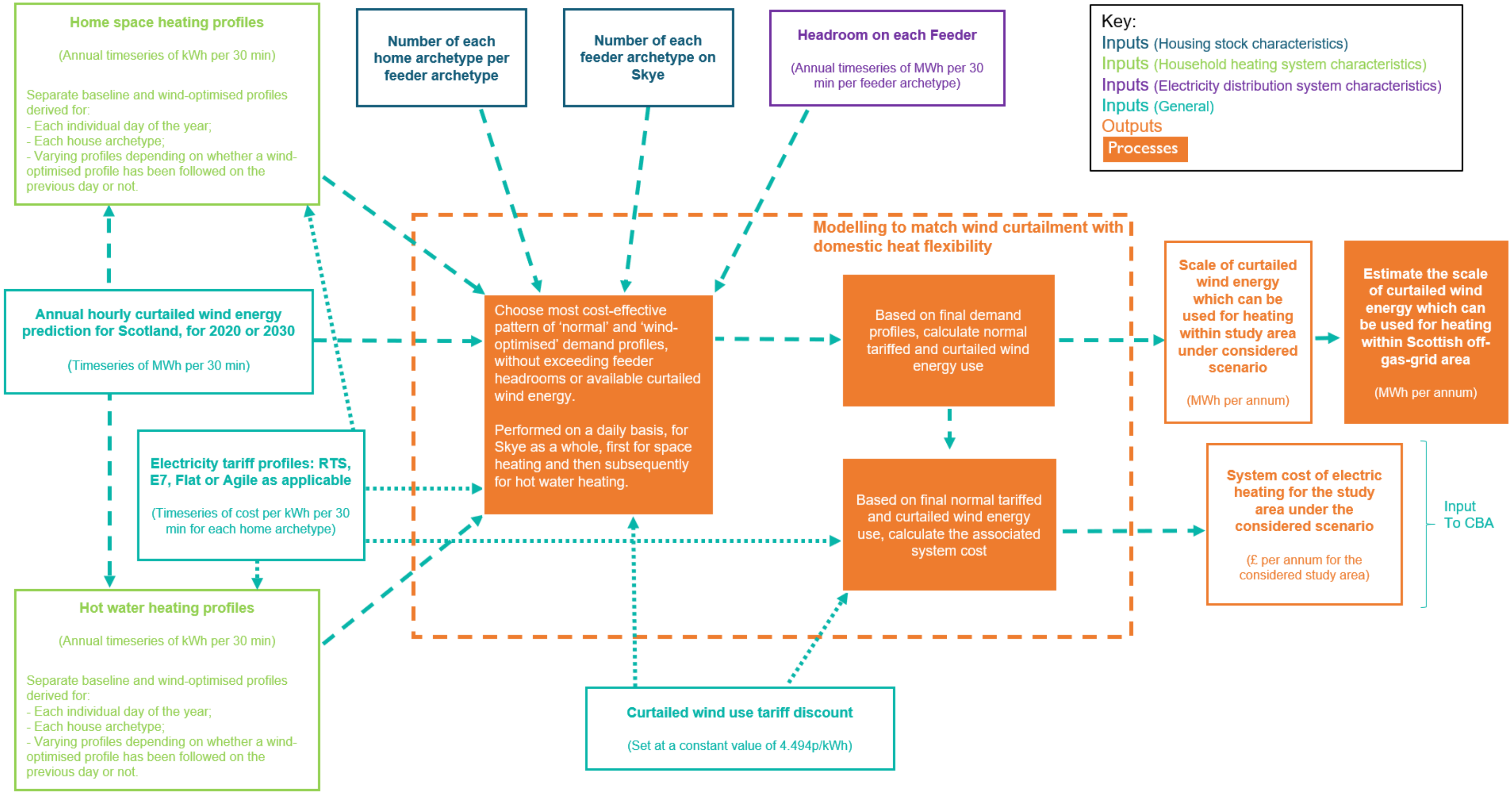

Figure 4 Overall model map

A modelling process was then used to match wind curtailment with domestic heat flexibility first for the base case and then the 4 different scenarios for both 2020 and 2030 (see Table 1). The findings were then scaled up for the whole of Scotland and used to inform a CBA.

2.2.1. Housing stock characteristics

The current housing stock on the Isle of Skye (our representative off-gas grid region) was grouped into six house archetypes, detailing property type, heating system type, floor area occupancy and space heating demand. The archetypes were based on analysis of 2011 census data as well as EPC data for the Isle of Skye. The 2030 house archetypes are evolutions of the 2020 house archetypes, anticipating expected changes over the coming decade, primarily:

- Changes in heating system type e.g. installation of air source heat pumps (ASHPs)
- Improvements in insulation levels leading to lower space heating demand.

The percentage of the housing stock represented by each archetype is the same in 2020 as in 2030. The archetypes are detailed in Table 2 and Table 3.

Table 2: 2020 House archetypes

Archetype	Space heating type	Hot water heating type	Number of occupants	Space heat demand (kWh)	Hot water demand (kWh)	Non-heating electrical demand (kWh)	% of housing stock
Detached bungalow 1	Fossil fuel, boiler and radiators	From main system	1	11,740	1,788	1,731	21%
Detached bungalow 2	Fossil fuel, boiler and radiators	From main system	2	17,850	2,526	4,603	20%
Semi-detached bungalow	Electric storage heating	Electric immersion, off peak tariff	1	10,287	1,788	1,731	13%
Detached house 1	Electric storage heating	Electric immersion, off peak tariff	2	12,940	2,526	3,541	13%
Detached house 2	Fossil fuel, boiler and radiators	From main system	4	21,000	4,001	6,336	21%
Semi-detached house	Electric storage heating	Electric immersion, off peak tariff	2	13,629	2,526	4,603	12%

Table 3: 2030 House archetypes

Archetype	2030 heating system	Hot water heating type	Improvements to Insulation	Number of occupants	Space heat demand (kWh)	Hot water demand (kWh)	Non-heating electrical demand (kWh)
Detached bungalow 1	ASHP	From main system	Loft in all homes applicable (~30%) and solid wall insulation	1	9,629	1,788	1,731
Detached bungalow 2	Fossil fuel, boiler and radiators	From main system	Loft in all homes applicable (~30%)	2	17,497	2,526	4,603
Semi-detached bungalow	Electric storage heating	Electric immersion, off peak tariff	Loft in all homes applicable (~30%)	1	10,113	1,788	1,731
Detached house 1	ASHP	From main system	Loft in all homes applicable (~30%) and solid wall insulation	2	10,766	2,526	3,541
Detached house 2	Fossil fuel, boiler and radiators	From main system	Loft in all homes applicable (~30%)	4	20,412	4,001	6,336
Semi-detached house	Electric storage heating	Electric immersion, off peak tariff	Loft in all homes applicable (~30%)	2	13,189	2,526	4,603

2.2.2. Household heating system characteristics

Each of the house archetypes were modelled with a digital twin of a similar real house (based on extensive real-world data gathered using PassivSystems technology) to produce annual forecasts of electricity demand for space heating and hot water production under each scenario. These scenarios included present-day simple controls using switched E7 or RTS systems, as well as predictive smart controls which optimise the delivery of occupant comfort against dynamic ToU tariffs. The smart controls were additionally incentivised to absorb demand at times of wind curtailment, to match as closely as possible the shape of the wind power curves while avoiding peak electricity rates for consumers. Crucially, the modelling accounted for multiple factors including building thermal inertia, detailed characteristics of heat pumps and hot water tanks, and the tolerance of occupants to having their homes overheated to absorb excess generation.

2.2.3. Electricity distribution system characteristics

The low voltage (LV) distribution network on Skye was characterised into 20 feeder archetypes, each with differing secondary substation capacities and number of customers. These were developed based on data provided by SSEN for the region.

The changes to heating systems and building fabric (taken into account in the 2030 house archetypes) provide updated electrical load profiles for each house archetype to be generated for both the flat/E7 scenario and the Dynamic ToU tariff scenario. Aggregating these profiles allows a new peak load for each feeder archetype to be identified. For the five feeder archetypes where network limits were exceeded in either the flat or Dynamic ToU tariff cases, we have assumed that network reinforcement would occur, upgrading the secondary substation transformer to the next standard size (e.g. from a 25kVA to a 50kVA).

2.2.4. Matching wind curtailment with domestic heat flexibility

The curtailed wind energy which would be cost-effective to absorb through matching wind curtailment[5] with domestic heat flexibility has been modelled for each relevant scenario. When evaluating cost-effectiveness, use of curtailed wind energy was assumed to be incentivised by a cost benefit to the household. The actual incentivisation payment could vary between zero/marginal up to a likely maximum ~4.9p/kWh which is what the ESO currently pays to curtail wind. Each home and day across the year has been considered individually, each time selecting the most cost-effective option out of the available space heating and hot water 'normal' baseline and 'wind-optimised' energy demand profiles, whilst ensuring the feeder headroom limits and total available curtailed wind energy are not exceeded at any point.

2.3. Cost benefit analysis method

The CBA scales up the modelling outputs to cover all of off-gas grid Scotland to determine the total discounted costs and benefits of each scenario.

The CBA factors in the cost of smart control, including the costs associated with promotion, the hardware, the installation, and ongoing smart service provision. The costs associated with the implementation of time of use tariffs (e.g. systems necessary to settle customer half hourly), the costs of the low-carbon technologies (e.g. heat pumps and insulation) were not factored into the CBA as it is assumed these will be implemented regardless of whether the 4D Heat concept is implemented. This analysis was informed by desk-based research.

The key outputs of the CBA include:

- Avoided wind constraint payments, which can be shared directly with the homes providing the response and /or the ESO.
- Household savings (for participating households) attributable solely to optimised controls
- Household benefits (for participating households) from curtailed wind consumption incentivisation payments
- Environmental benefits due to the avoidance of curtailed wind (avoided CO_2 and NO_x emission benefits) – these are based on the reduction in energy that would have otherwise been used outside of times of curtailment.
- Societal benefits due to the avoidance of curtailed wind[6].
- The system-wide benefits for each scenario, taking into account all of the above costs and benefits.

The CBA conducted is relative to the current status quo - termed the 2020 and 2030 base cases (cases A and D, respectively). The CBA seeks to determine if the investment required for the different scenarios (i.e. fitting of smart controls) is less than the benefits realised.

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[5] Forecast wind curtailment provided by National Grid ESO based on modelling from Two Degree pathway - Future Energy Scenarios 2019.
[6] The societal benefits have been added into the CBA to recognise the broader societal benefits of reducing curtailed wind power. For example, these include increasing wind power investor community confidence in deploying future projects and possible broader societal benefits arising from increased system security, reduced network charges and the resultant fuel poverty reduction impact this may have. The benefit was valued at 0p/kWh so therefore have no impact on NPV or payback period.

3. Results and findings

The modelling demonstrates that up to 540GWh of wind (approx. 9.2% of forecast curtailed wind) can be absorbed by off-gas grid domestic heating across Scotland in 2030. This equates to a saving of £24m/year in wind constraint payments and a further £2m/year in environmental and societal benefits. Smart controls fitted to make this possible result in an additional £22m/year saving for households. Implementing this scheme in 2030 could result in a payback of ~1 year and a 10-year system wide NPV of £300m.

3.1. Matching wind curtailment with domestic heat flexibility

3.1.1. 2020 Results

The annual costs and curtailed wind absorption due to electric heating and hot water across Skye under each 2020 scenario are presented in Table 4. The results were produced for the relevant electrically heated homes on Skye then linearly scaled up to all off-gas grid Scotland.

It is noted that wherever cost-effectiveness is referred to within this analysis, this refers to cost-effectiveness for the system as a whole, rather than the price seen by individual homes.

Table 4: Scenario results for all off-gas grid Scotland in 2020

Scenario	No. homes with smart controls fitted	Annual electric space heating and hot water cost *	Annual cost change relative to the base case		Annual curtailed wind absorption	Percentage of curtailed wind absorbed
		£ million	%	£ million	GWh	%
A1: 2020 Base case	-	178.1	-	-	-	-
B1: Smart controls only (RTS)	45,700	174.6	-2.0%	-3.5	30	2.2%
C1: Optimisation to ESO wind constraints (RTS)	45,700	173.1	-2.8%	-5.0	54	4.1%
B2: Smart controls only	127,600	172.1	-3.4%	-6.0	154	11.7%
C2: Optimisation to ESO wind constraints	127,600	168.0	-5.7%	-10.1	221	16.8%

*The cost for non-wind-optimised Scenarios B1 and B2 assume a zero price discount for any absorbed wind energy above the base case, whilst Scenarios C1 and C2 assume a price discount of 4.494p/kWh wherever curtailed wind energy is absorbed above Scenario B1 and B2 respectively.

The following key observations are made:

- **Up to 221 GWh of wind can be absorbed by domestic heating across off-gas grid Scotland in 2020.** This equates to ~16.8% of forecast curtailed wind, and occurs under a scenario where smart controls are installed and explicit wind consumption is incentivised. This is evidenced by Scenario C2. The reduction in consuming grid mix electricity results in avoiding up to 42 gigatons of CO_2 emissions.
- **Storage heaters offer greater wind absorption potential than immersion heaters:** This is mainly due to the larger energy demand of the storage heaters. It is also in part due to the effect of storage heaters spreading heating throughout the day (when there is curtailed wind) rather than only at night (during the usual cheap rate tariff period). Storage heaters charging up even by small amounts during the day also results in them operating more efficiently.
- **Transitioning from RTS to E7 with smart controls increases wind absorption and reduces cost:** It is to be expected because the E7 with smart controls homes can be controlled to optimise wind use, whilst the RTS homes cannot. Some benefit occurs even without specific wind-optimisation incentives due to the modelled demand profiles under E7 smart control being higher than the modelled RTS demand profiles during some periods of curtailed wind under the RTS scenario. This is evidenced by comparing Scenario B1 (67 % of homes RTS, 33 % of homes E7 with smart controls) with Scenario B2 (12 % of homes RTS, 88 % of homes E7 with smart controls): Scenario B2 leads to an additional 125 GWh of wind absorption (an additional 9.5 % of the total curtailed wind across Scotland) and cost reduction of 1.4 % compared to Scenario B1. Similarly, comparing the equivalent wind-optimised Scenarios C1 with C2, Scenario C2 leads to an additional 167 GWh of wind absorption (an additional 12.7 % of the total curtailed wind across Scotland) and cost reduction of 3.0 % compared to Scenario C1.

3.1.2. 2030 Results

The annual costs and curtailed wind absorption due to electric heating and hot water across off-gas grid Scotland under each 2030 scenario are presented in Table 5.

Table 5: Scenario results for all off-gas grid Scotland in 2030

Scenario	No. homes with smart controls fitted	Annual electric space heating and hot water cost *	Annual cost change relative to the base case*		Annual reduction in wind curtailment	Percentage of curtailed wind absorbed
		£ million	%	£ million	GWh	%
D: 2030 Base case	-	177.1	-	-	-	-
E: Smart controls only	96,100	170.4	-3.7%	-6.6	92	1.6%
F: Dynamic ToU tariff	222,600	155.6	-12.1%	-21.5	321	5.5%
G: Optimisation to ESO wind constraints	222,600	165.7	-6.4%	-11.4	164	2.8%
H: Dynamic ToU tariff + Optimisation to ESO wind constraints	222,600	144.5	-18.4%	-32.5	540	9.2%

*The cost for non-wind-optimised Scenarios E and F assume a zero price discount for any absorbed wind energy above the base case, whilst Scenarios G and H assume a price discount of 4.494p/kWh wherever curtailed wind energy is absorbed above Scenario E and F respectively.

The following key observations are made:

- **By 2030 the forecasted annual volume of curtailed wind is over three times greater than total space heating and hot water demand of all electrically heated homes in off-gas grid Scotland.** Therefore, even with 100% flexibility not all the curtailed wind could be consumed. However, it should be stressed that this finding is based on *off-gas grid Scotland* only. The impact could be greater if homes on the gas grid transition to electrified heat, or if heat assets are blended with other domestic flexibility solutions such as smart charging of electric vehicles.
- **Up to 540GWh of wind can be absorbed by domestic heating across off-gas grid Scotland in 2030.** This equates to ~9.2% of forecast curtailed wind. This occurs under a scenario where smart controls are installed, explicit wind consumption is incentivised, and Dynamic ToU tariffs are used. This is evidenced by comparing Scenario H with the Base Case – and demonstrates the ultimate size of the prize when all levers are pulled, spanning home assets, supply tariffs and ESO incentive. The reduction in consuming grid mix electricity results in avoiding up to 26 gigatons of CO_2 emissions .
- **Switching to a dynamic ToU tariff significantly increases wind absorption, even without specific wind-optimisation incentives being used[7]**. This is evidenced by comparing Scenario E and F: an additional 229GWh is absorbed merely by switching tariff. This is due to the correlation between wholesale price and wind generation: the Dynamic ToU tariff is cheaper during periods of high wind energy due to the negligible variable cost of wind generation. **It is striking that such volumes can be achieved merely by achieving a change in energy supply tariff, without any additional ESO action required.**
- **Implementing a specific wind-optimisation incentive, in addition to Dynamic ToU tariffs, significantly increases wind absorption**. Comparing Scenario H and F shows that an explicit 4.494p/kWh price incentive leads to an additional reduction of 218GWh of wind curtailment, increasing the percentage of avoided wind curtailment from 5.5 % to 9.2 %.
- **In all cases the storage/immersion heater homes are shown to absorb substantially more curtailed wind than the heat pump homes.** For example, under Scenario H, the magnitude of absorption from the storage/immersion heater homes is 3 times greater than the wind absorption at the heat pump homes. This is mainly due to the larger energy demand of the storage heaters. It is also in part due to the storage heaters being additionally incentivised to use curtailed wind energy due to spreading heating throughout the day (when there is curtailed wind) rather than only at night (during the usual cheap rate tariff period). This leads to more efficient operation.
- The **key limiting factors for wind absorption (beyond commercial factors) are occupants' tolerance of overheating** (a maximum of 2°C above usual setpoint temperatures was allowed for in the modelling) and the availability of headroom in the hot

[7] Tariff parameters:

- RTS: 3am to 7am and 1pm to 4pm at 8p/kWh, the remaining time at 16 p/kWh;
- E7: 12am to 7am at 8p/kWh, the remaining time at 16 p/kWh;
- Flat: a constant rate of 14p/kWh;
- Dynamic ToU: a dynamic time of use tariff, published day-ahead, consisting of wholesale electricity price (multiplied by 2.2) plus DuOS charges (12p added between 4pm and 7pm local time), with resulting values being capped at 33.33p. The tariff used in this analysis follows the pricing algorithm as used by Octopus Energy for their Agile tariff.

water tank over and above normal hot water provision. Note this applies in both the 2020 and 2030 scenarios.

- **Actions taken to consume wind can have impacts lasting more than one day-ahead.** The smart control systems regularly reacted to price signals as well as the availability of curtailed wind more than 24 hours in advance. These actions tend to diminish in magnitude the further out they are taken. However, on aggregate even small actions can add up to a significant response on the portfolio level. This demonstrates the importance of accurately accounting for the long duration thermal time constants of households and the requirement for an optimised lookahead control system to be able to take advantage of this, ideally at an aggregate portfolio level to absorb wind most effectively. Note this applies in both the 2020 and 2030 scenarios.

3.2. CBA results

The CBA investigated the benefits associated with avoiding wind constraint payments, environmental benefits and the benefits derived from smart controls versus the upfront and ongoing cost of the smart controls which enable the value streams to be accessed. The key findings of the CBA include:

- Implementing the 4D Heat concept may result in a system-wide **payback period anywhere between 1 to 7 years in a 2030 implementation scenario and 4 to 7 years in a 2020 implementation scenario**. The payback at the household level is always longer than the system-wide payback since the household does not have access to all the value streams. Depending on the scenario and the way wind curtailment savings are shared between the ESO and the participating households, this varies from a 30% longer payback period to a >300% longer payback period for the household versus the system. Therefore, energy market design is a consideration when determining how to share the benefits with customers, both those directly participating in providing flexibility, and the broader customer base through reduced Balancing Services Use of System charges.
- **The benefit from fitting smart controls is in many cases the largest source of system-wide value.** On average across all scenarios 50% of the overall system value is derived from the fitting of smart controls. The value from fitting smart controls (aside from providing a mechanism to potentially access specific curtailed wind incentive revenue streams) comes from optimising heating profiles to conserve energy. In the case of homes with ToU tariffs, further value is delivered by best aligning periods of demand with low wholesale prices.
- **The total system value derived from savings on wind constraint payments makes up close to half of the overall benefits.** On average across the scenarios 42% of the total system value arises from avoided constraint payments. If the ESO retains the avoided curtailed wind payments, rather than providing them to households as an incentive, the payback period on smart controls for households is doubled.
- **Less than one-tenth of total value is derived from avoided CO_2 emissions.** The environmental & societal benefits, which account for 8% on average, across all scenarios, of the total system value, are comprised largely (>95%) of the value associated with avoided CO_2 emissions. The remaining <5% is comprised of avoided NO_x emission benefits. The CO_2 and NO_x benefits arise due to the reduction in the use of grid mix electricity at times when wind is not being curtailed. UK Government (BEIS and DEFRA) figures have been used to calculate the cost of CO_2 and NO_x.

The 2020 cases for fitting smart controls and helping consume otherwise curtailed wind are in most cases attractive as far as energy efficiency measures are concerned. The payback for the household in every case is greater than ~5.5 years. In the most extreme cases where we assume homes explicitly try consume otherwise curtailed wind but get a negligible payment to do this may result in an average payback period to households in the region of 20 years. However, in most cases these paybacks are shorter than other efficiency improvements that a homeowner could invest in, e.g. double glazing and solid wall insulation. And whilst measures like double glazing have other perceived benefits (lower maintenance, etc), smart controls also offer other non-financial benefits such as improved control and thermal comfort levels.

In the 2030 cases, there is more value to be gained by implementing a program of smart control. Switching homes to a Dynamic ToU tariff with smart control will result in significant cost savings with a payback period of less than 4 years. There is also the added benefit of the ESO indirectly saving on constraint payments. This is because cheap tariff periods, when the homes smart control will aim to drive up consumption, are largely correlated with times of wind curtailment.

3.3. Consumer perspectives

Over 1.1 million residential assets are being employed for demand side flexibility (DSF) in Europe today, showing customers will participate in schemes of this nature providing an appealing customer proposition is present. In almost all existing schemes there is financial benefit to the customer for participating. Most commonly this is delivered through energy bill savings but some schemes instead offer an upfront or ongoing financial incentive. Additionally, most propositions offer non-financial benefits such as energy insights, better heating system control, remote diagnostics (and associated reliability and maintenance benefits) and “feel good” soft benefits such as contributing to decarbonisation and system security. Typically, these non-financial benefits alone are not sufficient to incentivise a customer to participate but collectively make for an attractive proposition.

Effective customer propositions can also address customer concerns on:

- Third party control
- Trust in the technology
- Risk of higher bills
- Cyber security
- Disruption to lifestyle

These concerns are alleviated through initially engaging with the customer through a trusted route, ensuring that the customer always has an override option, reducing all costs to the customer to as great an extent as possible and ensuring that all installation and ongoing communication is smooth and efficient.

In the UK, multiple demonstrator projects funded by BEIS and Innovate UK are testing the optimal consumer proposition for British consumers, and to what extent consumers should be exposed to changing price signals; this ranges from ToU tariffs through to energy-as-a-service (EaaS) models. Industry has not yet converged on a single solution.

4. Conclusions and recommendations

Smart electric heating can unlock the potential of wind that would otherwise have been curtailed, and market-led time of use tariffs are the primary mechanisms to access this. 4D Heat demonstrates the need for whole system thinking and the importance of end use customers in managing issues at a system-wide level.

4.1. Conclusions

The 4D Heat project demonstrates that engagement with domestic electric heating customers to access their heat flexibility can provide substantial cost and CO_2 savings, and result in reduced curtailed wind generation. Based on the assessment of Skye and extrapolating to Scotland, up to 17% in 2020 and 9% in 2030 reduction in forecasted curtailed wind is achievable.

There are, however, fundamental limits to the use of electric heating for managing curtailment, and this study estimates that by 2030 the magnitude of the curtailed wind above the B6 boundary is more than three times greater than the total annual space heating and hot water demand of all the electrically heated homes in off-gas grid Scotland. Therefore, even with 100% of heating flexibility being made available, this will only be part of the solution.

This work has shown the importance of all three mechanisms investigated in relation to accessing domestic heating flexibility (see :

1. Smart controls which optimise heating systems: These provide the means to control the heating devices and optimise supply, delivering financial and environmental benefits in their own right. Alone, they reduce wind curtailment by up to 4.1% in 2020 and 1.6% in 2030 and provide annual cost savings in heating bills of up 3.7%. They offer a system-wide payback period of around 7 years. Smart controls also help improve thermal comfort levels in the home.

2. Time of use tariffs: The analysis demonstrates that market led ToU tariffs provide the strongest signal for households to modify their heating loads in response to the grid supply mix. This provides households with annual cost savings in heating bills of up to 12% in 2030, and incentivises the use of curtailed wind due to periods of high wind generation (and therefore constraints) having a strong correlation with low price periods. Dynamic time of use tariffs increases the avoided wind curtailment by a factor of 4 compared to smart controls alone, helping avoid up to 5.5% of the total wind curtailed in 2030 delivering a system-wide payback period of around 1.6 years.

3. Direct wind curtailment incentives: directly driving wind consumption by offering homes a financial incentive to increase demand at times of curtailment results in further significant system wide benefits. This results in a further 40-80% increase in the total amount of curtailed wind absorbed compared to the cases where such an explicit wind

consumption incentive is not present. Smart controls are crucial in unlocking this value stream in a way that is acceptable to occupants, for example by limiting the amount of overheating due to curtailed wind absorbance. Combining smart control, time of use tariffs and direct wind curtailment incentives offers a system-wide payback period just over 1 year.

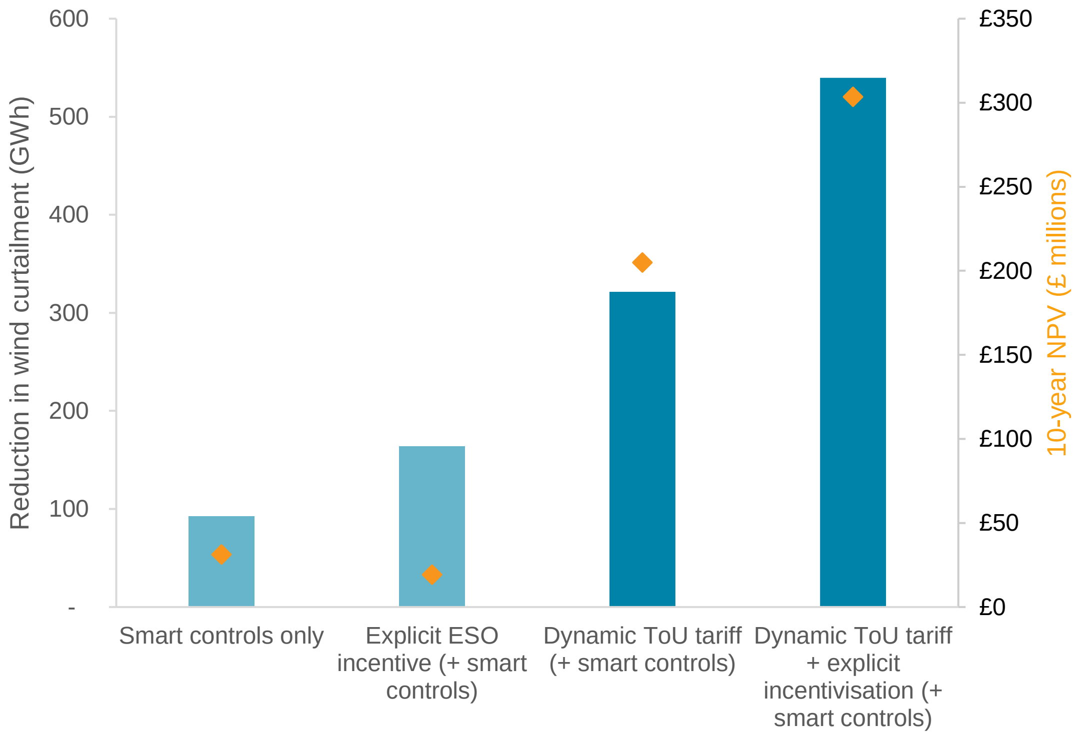

Figure 5: Reduction in wind curtailment (bars) and 10-year NPV (diamonds) in 2030 in response to the different mechanisms investigated.

There are precedents both in the UK and across Europe that show that customers are willing to engage with all three of: smart controls, ToU tariffs and direct provision of flexibility. The evidence shows that these propositions can be successfully delivered without negatively impacting customer comfort levels or behaviours.

4.2. Recommendations

4D Heat identifies the need to engage more closely with households in a way which allows them to deliver benefits at a system-wide level. The recommendations are therefore based around improving this whole system thinking approach, making use of current and future market mechanisms to access demand side heat flexibility. Historically, a system-wide approach has often referred to improved coordination between the transmission and distribution network. But the findings of 4D Heat highlight that alignment between ESO and DSO alone is insufficient: instead, ESO and DSO are compelled to more proactively engage with wider energy market reform and end user propositions.

The following recommendations are made:

- **Being a proactive voice on energy supply market reform:** 4D Heat's modelling shows that transitioning to dynamic ToU tariffs can reduce wind curtailment. This is significant. It suggests that wind curtailment can be reduced to a large extent by energy supply market reform, without the ESO/DSO incurring additional costs. As a result, the ESO and DSO have a case to promote innovation in the energy supply market – for instance via mandatory half-hourly settlement, or addressing barriers to energy-as-service propositions. This further means barriers such as deploying smart meters in remote parts of the Scottish Highlands also need to be addressed.

- **Supporting the evidence base for smart controls:** Alongside the promotion of variable tariffs, measures are needed to ensure that domestic heat assets are equipped with smart controls to enable access to heat flexibility. It is in the interest of the ESO and DSOs to ensure that smart controls are part of any policy incentive e.g. heat pumps installed under Clean Heat Grant and Green Homes Grant should be conditional on having smart controls in place that have sufficient capability to access demand flexibility without compromising occupant comfort requirements.
- **Enabling industry innovation:** There is an opportunity for the wind industry to explore more innovative models, where constraint management is a core consideration in the development process and business model of the wind farm supplier. This might include engaging with suppliers and/or local end users though novel local energy market mechanisms to include residential demand side flexibility as part of their core operation. ESO and DSOs can support this by sharing network constraint data, and adopting a 'market enabler' role on network capacity trading.
- **Ongoing ESO and DSO service reform**. The ESO and DSOs are exploring routes to broaden participation in their services; for instance, via the Balancing Mechanism Wider Access workstream. For DSO services, 4D Heat specifically recommends developing mechanisms for dynamic portfolio allocation (customers entering/exiting portfolios), clarifying baseline requirements (against which performance is measured), and considering framing of availability windows (to avoid biasing against heat). This recommendation dovetails with ongoing initiatives in the Open Networks project. In addition, the domestic heat market would benefit from further empirical demonstration to identify additional real-life barriers which may be difficult to identify or understand from a desk-based review. Often it is only through learning by doing that the full suite of barriers come to light.
- **Addressing RTS:** There is a widely acknowledged need to address the retrofit and market barriers challenge associated with Electric Storage Heaters controlled by RTS in advance of the planned decommissioning in March 2023. Customer journey mapping is required to articulate the necessary technical interventions e.g. rewiring, smart control and smart metering installation. This mapping can be used to identify the range of options available to energy retailers (there are dependencies on the Smart DCC having provisioned a reliable wireless connection in advance of SMETS2 metering systems being installed). Installing smart control systems onto Electric Storage Heaters will still require retrofit activity however the value provided to the end customer in terms of improved comfort and savings should outweigh this. Effort is required by the sector to ensure that the transition towards a more digitalized energy system doesn't leave these customers behind.
- **DSO Business Planning:** There may be a role for DSOs' *Vulnerable Customer* strategies to help make fuel-poor homes heat-flexibility ready. This would both activate more households to address constraints, whilst also cost-efficiently address fuel poverty reduction. A critical qualifier is that the DSO should focus wholly on promoting heat flexibility *readiness* rather than directly favouring heat flexibility operationally during procurement. This is about enabling heat flexibility participation rather than favouring it. This theme might be pursued under the RIIO-ED2 business planning process.

Further research and analysis are required to provide a more robust evidence base for future policy development. Areas to explore include:

- **Adopting a whole-home approach**. Most domestic aggregators treat heat flexibility solutions alongside other domestic flexibility sources – for instance electric vehicle charging and battery storage. This asset blending both tends to be more cost-effective and also to unlock greater flexibility. As such, it is recommended that future models assess heat flexibility alongside other energy flexibility solutions in the home.
- **Assessing the actual performance** of domestic heating responding to wind constraints. This could include conducting a real-world trial to test out the customer impact of engaging with a new heat service that will be designed to provide comfort as well as cost savings. The control system deployed will learn the thermal characteristics of the homes and will be designed to maintain customer led comfort levels, while optimising wind utilisation at an aggregate level (coordinating the response across a portfolio of homes).
- **Understanding the impact of diversity.** The movement of all households from a flat electricity tariff onto a ToU tariff is likely to increase peak demand around tariff boundaries, but the impact is hard to predict due to diversity in customer behaviour and in tariff parameters between different energy suppliers. As the penetration of heat flexibility increases, diversity is lost, but on the other hand smart controls have the potential to mitigate demand peaks. Further understanding of these market maturation effects is required, with a much larger sample of household types and occupancy profiles.
- **Spatial assessment of wind constraint management**. Whilst the focus of this work has been on the B6 (England-Scotland) boundary, constraints also exist within the transmission network in Scotland as well as at the distribution level. Further analysis could be conducted to examine the spatial distribution of heat flexibility potential in relation to constraint locations. This would also allow assessment of distribution level impacts of heat flexibility engagement, and the synergies and possible conflicts with flexibility being deployed by the ESO.
- **Comparison of residential flexibility with alternative solutions.** Evaluate the costs of paying for residential demand response services against network reinforcement and other solutions such as grid scale battery storage or hydrogen electrolysis.