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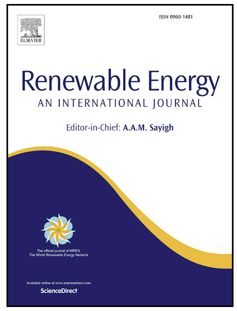

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Value of Demand Flexibility for Managing Wind Energy Constraint and Curtailment

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Abstract: The dispatch-down of excess wind energy is a growing concern especially for countries integrating high levels of variable-renewable energy. Demand flexibility presents an opportunity to move consumer loads to periods of excess wind energy, which could provide numerous values to the system. While previous research has focused on managing wind energy curtailment (a system-wide issue), much wind energy is rejected due to constraint (a local issue) and hence can only be resolved by local load on-demand. This paper provides a framework to assess the value of demand flexibility for managing wind energy constraint and curtailment. A methodology to determine the optimal number of subscribers to yield sufficient reduction in excess wind energy while ensuring reasonable cost-savings for the subscribers is developed. Analysis shows that this optimal number of subscribers could provide a 67% reduction in constraint and a 74% reduction in curtailment. Consumers can save up-to £220 per year, depending on their priority in the dispatch process. A 10-MW wind farm could earn £19,400 annually from avoided curtailments. System operators could save up-to 78% on constraint payments. The paper also assesses the network impact of flexible loads and provides a methodology for calculating the heat-pump hosting capacity of the grid.

Keywords: Wind Dispatch-down, Fuel Poverty, Constraint Payments, Wind Distribution optimization, Network Hosting Analysis, Peak Demand Reduction.

Nomenclature

ROC – Renewable Obligation Certificate	P2H – Power to Heat
SNSP – System Non-Synchronous Penetration	TSO – Transmission System Operator
MinGen – Minimum Conventional Generator	BSP – Bulk Supply Point
HighFreq – Emergency High Frequency	DAM – Day Ahead Market

1. Introduction

The global call for decarbonisation to address climate change combined with the rapidly falling costs of renewable generation has increased wind and solar generation uptake over the past decade. Renewables accounted for 42.9% of the UK electricity generation in 2020 [1]. However, there are challenges associated with integrating high levels of renewables into the grid due to their variable and intermittent nature. Hence, a significant amount of wind generation is dispatched down (dumped). The UK spent a total of £649 million in constraint payments between 2011 and 2019 to reject 8.7 TWh of electricity [2]. Between 2020 and 2021, £350 million in constraint payments were paid to wind farms in Scotland for dumping 5.2 TWh of wind energy [3].

For the electricity grid to be reliable, it must have a continuous power supply and a stable voltage and frequency. Grid operators have to carefully manage the grid to ensure that demand and supply are instantaneously balanced [4]. Generators may be asked to reduce their output to a level lower than was agreed in the electricity market. This happens when more electricity is being generated than required [5]. Dispatch-down of conventional generators have less financial impact than for wind power generators [6]. When a fossil-fuel generator reduces its output, there is a cost-saving in the system due to reduced fuel cost. However, wind farms do not have fuel cost and hence any reduction in output will mean significant financial loss. Furthermore, they also lose revenue from subsidies such as the Renewable Obligation Certificates (ROC) [7].

Wind farms are dispatched down for two main reasons: constraint or curtailment [8]. Dispatch-down for curtailment is due to systemwide balancing issues such as the maximum non-synchronous penetration (SNSP) that can be allowed on the grid at any given time, emergency high frequency (HighFreq) events, minimum conventional generators (MinGen) that must run to keep the system stable, system stability (inertia, dynamic and transient stability), operating reserve and voltage control requirements [8]. Hence system operators can reduce the output of any renewable generator on any part of the network to keep the system stable [9].

On the other hand, constraint refers to situations when wind energy is dispatched-down because of localised network issues such as backflows, voltage issues, and thermal limits [10]. In other words, more electricity is being generated than can be consumed in a particular area or transported from that area to the rest of the grid. In this case, the constraint can only be alleviated by turning down controllable wind or solar generation in that area (defined by the System Operator as a constraint group) [11]. Constraint groups are used to group wind and solar farms with similar effectiveness in reducing the level of a transmission constraint. Wind / solar farms connected at the same transmission substation would usually have similar effectiveness and are allocated to the same constraint group [11].

In Ireland, wind farms are paid constraint payments for the loss of market access. This cost is passed on to consumers who end up paying for electricity not consumed. In contrast, wind farms are not compensated for curtailments [12]. However, this might change following Article 13 of the EU Clean Energy Package [13], which requires financial compensation for curtailments. Curtailment in the Irish electricity system is carried out on a pro-rata basis [11].

Demand Flexibility is defined as the capacity to shift the time when energy is drawn from or exported to the grid by behind-the-meter resources in response to an external signal (such as electricity price) [14]. This is achieved either by using storage or changing the activity time [10]. Consumers can move their electricity demand to times of excess wind energy and help to manage constraint and curtailment [15,16]. The solution to constraint is local load-on-demand, while the solution to curtailment is a system-wide increase in load.

Allowing behind-the-meter consumer loads to manage this excess wind energy could help fulfil several social needs, for example, tackling fuel poverty. Research into the effect of wind farms on surrounding fuel poor rural communities showed no positive impact of the windfarms towards the neighbouring fuel poor communities while they do have some corporate social responsibilities [17]. Distribution of excess wind energy (particularly managing constraints) provides the opportunity for wind farms to make a positive impact on their local community, boost social acceptance of wind energy [18] and also provide additional revenue to the wind farms.

Excess wind energy is a finite resource and without intervention, maybe largely monetised by affluent households with better access to capital, automation technologies or who may be favoured by aggregators [10]. Distributing excess wind energy to fuel poor or low-income households would help to reduce the energy cost for these houses [19]. This paper investigates; how much excess wind energy dispatch-down could be reduced? How could the excess energy be shared? And what are the benefits to the stakeholders?

2. Literature Review

There has been an ongoing debate on the utilisation of excess wind energy for heating. The two main contentions is whether to use it for providing electric heating or for producing green hydrogen for heating. In the UK, Heat pump has been identified as a major technology to decarbonise the heat sector based on its higher efficiency [20]. The UK government has consequently committed to installing 600,000 heat pumps per year by 2028 [21]. However, there are concerns about the capital cost and also the operating cost due to the high retail electricity price (18.16p/kWh) compared to gas (4.9p/kWh) and heating oil (5.52p/kWh) [22,23]. Excess wind energy at a reduced fee could help reduce energy bills, especially for fuel-poor households. Nevertheless, decarbonising the gas network has raised even greater concerns.

The cost of replacement fuel such as green hydrogen, used in full or mixed with fossil fuel to reduce carbon intensity, will be greater than if renewables were used for direct electric heating given the current economic structure [24,25]. This is because the wind-to-heat efficiency of heat pumps is six times that of hydrogen. Heat pumps have an efficiency of (200-400%) [26], whereas the efficiency of hydrogen for heating is at about 50% [27]. Furthermore, building a new hydrogen distribution infrastructure or repurposing the existing gas infrastructure will require huge investments and consumers will ultimately bear the cost [28]. Hence installing hydrogen-ready boilers now in the gas regions will risk locking consumers to an expensive fuel in the future since these devices usually work for over 20 years [29]. Either way, consumers in the rural off-gas areas may have no other suitable option of low carbon heat except installing heat pumps or other electric options [30].

A model for estimating the amount of curtailment in the system is provided in [31,32]. The study in [33] showed that a significant reduction in wind energy curtailment can be achieved by increasing the SNSP limit. However, [34] showed that this has limited value if SNSP is increased beyond 70 – 75%. Utility Scale storage has been used to manage curtailment [35]. In [36], various utility-scale battery capacities and configurations were investigated to determine their cost-effectiveness in reducing curtailment. The optimal duration of energy storage needed to absorb wind energy curtailment is investigated in [37]. A statistic model for optimal allocation of energy storage for reducing wind energy curtailment is proposed in [38]. Several demand-side strategies (tariff-based load shifting [39], electric vehicles [40], heat pumps and thermal storage [41], storage heaters [42] have also been investigated.

All these previous studies [31–43] have been based on managing curtailments. Constraint is a local issue, and hence only flexible loads within the constraint group can alleviate a constraint. Furthermore, wind farms are now increasingly located in groups (clusters) with a substation connected at a central point (commonly referred to as cluster substation). This helps to reduce the amount of lengthy individual overhead lines, which is both costly and has a detrimental environmental impact. It has also helped to improve access to the network for renewable energy projects [44]. However, locating wind farms in clusters is increasing the amount of wind energy constrained during times of low local demand [44].

A recent technical study showed that constraints could be reduced by network reinforcement or demand increase in the constraint areas [9]. The study in [45] showed that increasing transmission capacity can help reduce wind energy curtailment. However, It has become clear that the expansion of the transmission network cannot keep up with the pace of uptake in renewable generation [46]. Furthermore, as highlighted in [9], additional network investments is an expensive option and would increase energy bills for end-users. Hence, an increase in demand within constrained areas, such as the uptake of electrically powered technologies, is a likely way forward and could benefit all parties involved.

To the best of the authors' knowledge, there has not been a study assessing the value of using local behind-the-meter demand to manage wind energy constraint. This paper fills this gap by providing a methodology to determine the optimal number of subscribers that can manage wind energy constraint and curtailments, determining the value of such a scheme to the various stakeholders and assessing the impact on the distribution network.

3. Case Study

This study uses the Northern Ireland electricity system as a case study. Northern Ireland achieved 49.2% renewable electricity generation (85% of which is wind energy) in 2020, exceeding its target of 40% [47]. It has set a new target of 70% renewable electricity by 2030. It also plans to handle at least 90% SNSP by 2030 [48]. The system can currently handle up to 70% SNSP at any time [49]. Fig. 1 shows the percentage of dispatch-down of wind energy in Northern Ireland between 2011-2020. There has been a steady increase in dispatch-down as the penetration of wind energy increases. In 2020, about 15% of available wind energy was rejected [50]. Without demand flexibility, there will be more curtailment and constraint of wind energy as Northern Ireland strives to reach its 2030 targets. Furthermore, more than 90% of wind energy is connected to the distribution side of the network [51,52]. This presents opportunities for consumer-owned flexibility to be used to manage the variabilities, curtailments, and constraints locally.

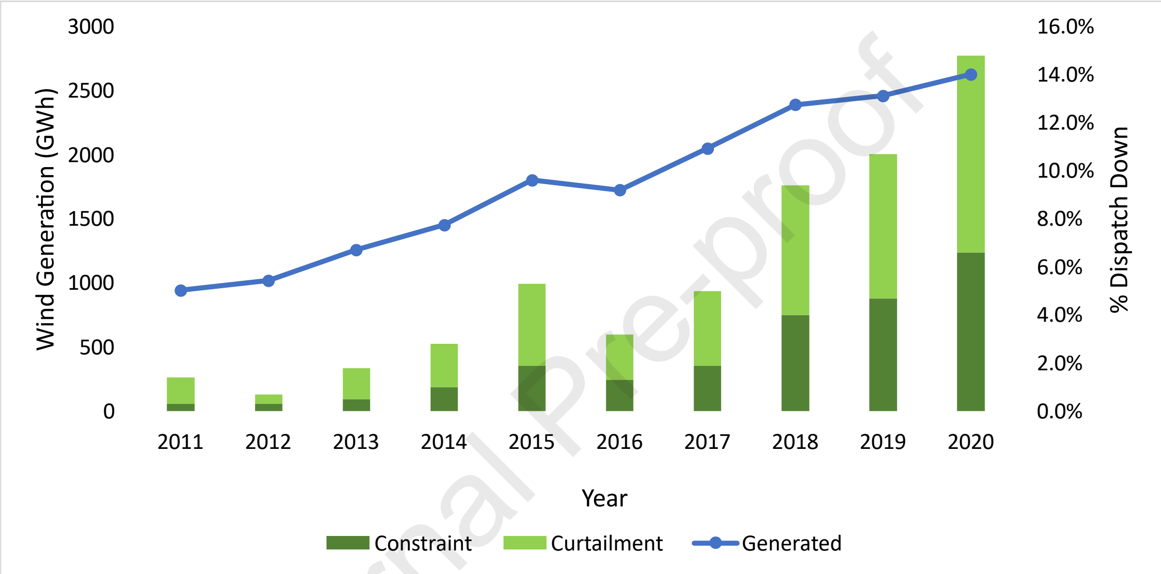

Fig.1. Annual wind generation vs constraint and curtailment.

Fig. 2 shows the dispatch-down availability curve and event duration curve. Over 100 MW of wind energy is dispatched down 10% of the time. These events can last for up to 40 hours. However, three-quarters of events last for less than 5 hours.

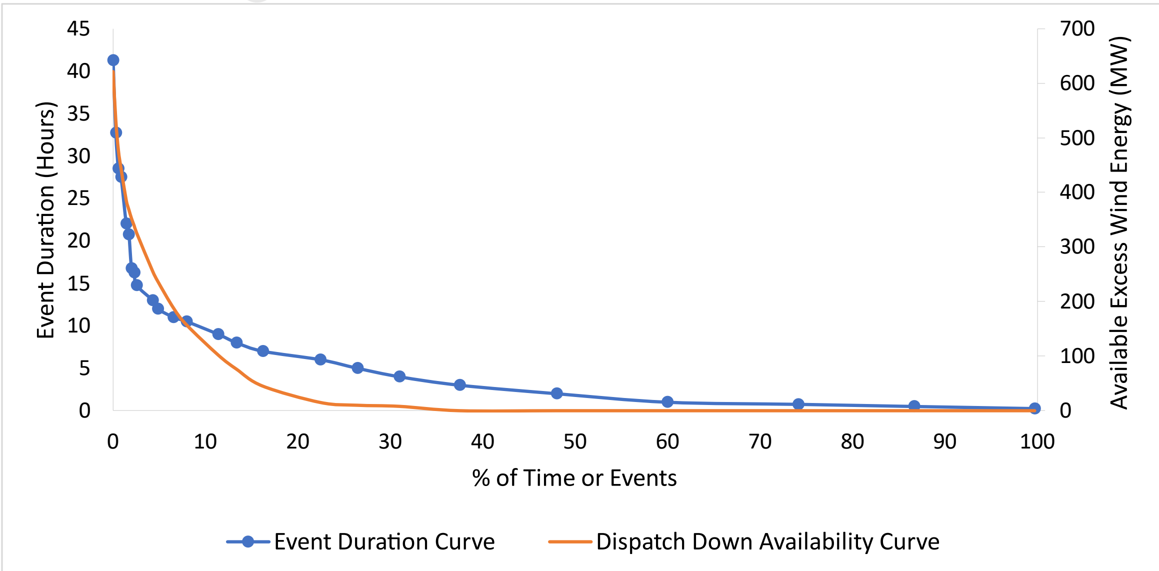

Fig. 2. Wind dispatch-down availability and duration curve.

There are four constraint groups in Northern Ireland. Curtailment and constraint values for each transmission node (bulk supply points) were derived using both the aggregate values from the 2019 report [53] and the forecasted nodal values in the 2016 curtailment and constraint report [54]. This was used to calculate the total constraint in each of the constraint groups. The results are presented in Fig. 3. An interactive version of this map can be found in [55]. Constraint group 3 is a subset of constraint group 2; hence, the total constrained wind energy for constraint group 2 is 89 GWh/Yr. (53 GWh/Yr. + 36 GWh/Yr. of group 3) [10]. Constraint group 4 refers to the whole of Northern Ireland. Hence constraint group 1,2 and 3 are subsets of Constraint group 4. However, in this work, the excluded set (houses not in constraint group 1, 2 or 3) will be referred to as constraint group 4. The time-series constraint profile for the individual constraint group was derived from the total constraint profile by multiplying it by the ratio of wind energy constrained in each group to the total constrained in the system. Hence, it is assumed that constraint occurs at the same time in each constraint group.

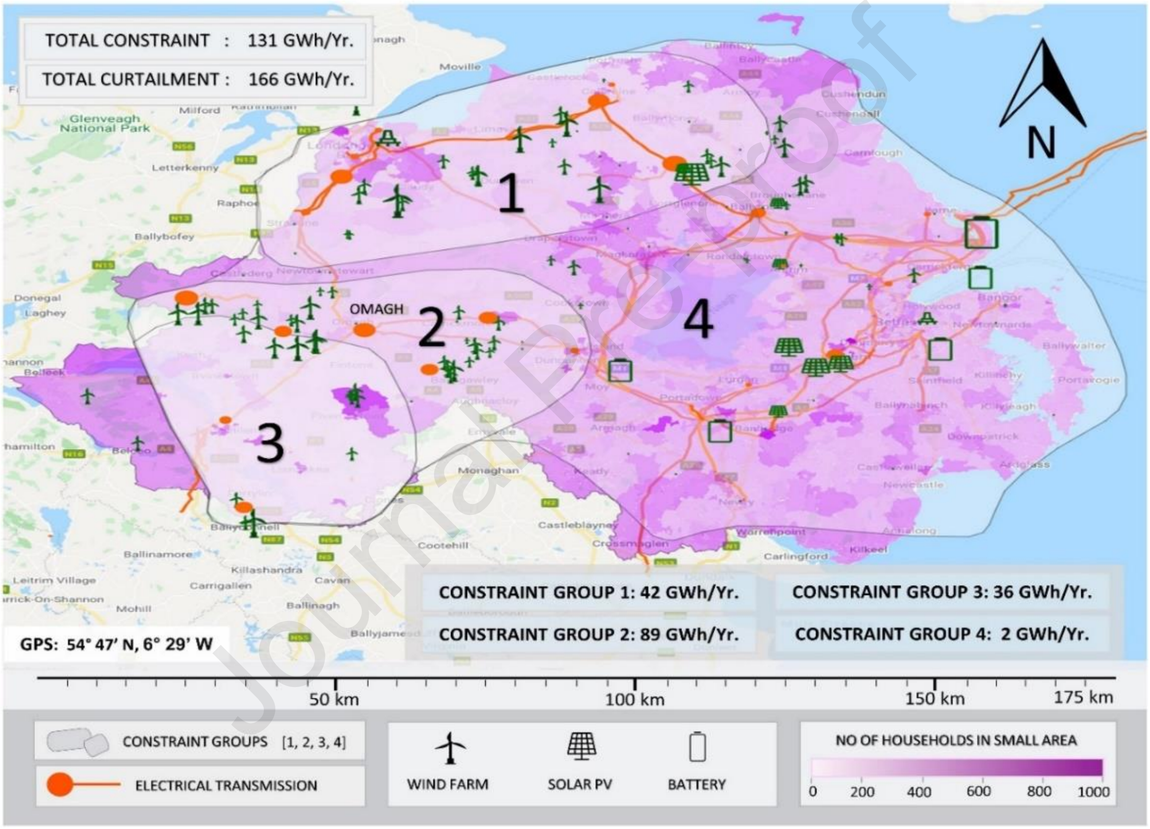

Fig. 3. Spatial distribution of wind farms and constraint groups in Northern Ireland.

The Omagh bulk supply point (BSP) in constraint group 2 was used as a case study for this investigation. A BSP is a point at which electricity is delivered from the transmission to the distribution system [56]. The BSP is made up of two 63/90 MVA transformers. There is about 126 MW of wind capacity connected at the BSP. 108 MW of this is controllable (i.e., is visible to the transmission system operator (TSO) and can be dispatched down). The reverse power flow limit of the 110/33 kV BSP is 90 MVA. This is the maximum amount of electricity that can be exported away from the substation to the rest of the grid. Given the limitations of the two 63/90 MVA transformers, any more would be constrained. Fig. 4. shows the average hourly available wind generation, the average wind energy dispatched down and the average substation reading for 2019.

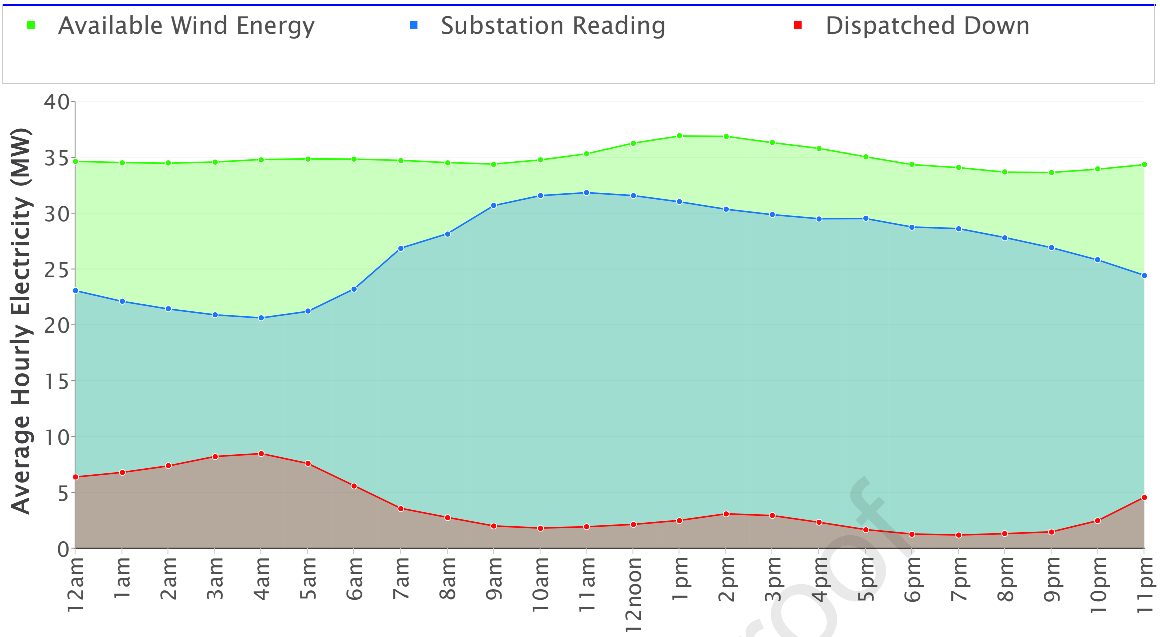

Fig. 4. Average hourly generation and dispatch-down at the Omagh substation.

4. Methodology

This section describes the methodology used to investigate the value of demand flexibility for managing wind energy constraint and curtailment. First, we developed a model for simulating the response of heat pumps to constraint and curtailment signals. Then we used this model to find the optimal number of subscribers that can participate in this scheme and investigate the benefits to the various stakeholders using the wholesale market price. We also investigate the impact of the demand response on the distribution network by performing a power flow analysis with a more detailed case study.

4.1. Demand Response Modelling and Simulation

Simulations are performed to determine the number of subscribers required to completely prevent the dispatch-down of wind energy in each constraint group. Simulations begin with one subscriber and continue until the excess wind energy is utilised. At the end of each iteration, the percentage reduction in dispatch-down and the average cost savings for the given number of subscribers is calculated. After each iteration, the number of subscribers is increased for the next iteration. For each iteration, simulation is performed in 15 minutes resolution. Fig. 5. shows the control logic for the demand response simulations.

When there is excess wind energy in the constraint group, the heat pump is turned on to charge the thermal storage of the individual homes. When there is a heat demand, the charged storage is used to meet the heat demand before the heat pump is turned on. The demand during the peak period is estimated from the demand the day before. The thermal storage is allowed to discharge during the day as long as there is enough energy reserve to meet the requirement of the peak period (4 pm – 8 pm). This ensures that the storage is effectively used to reduce the consumer's electricity bill.

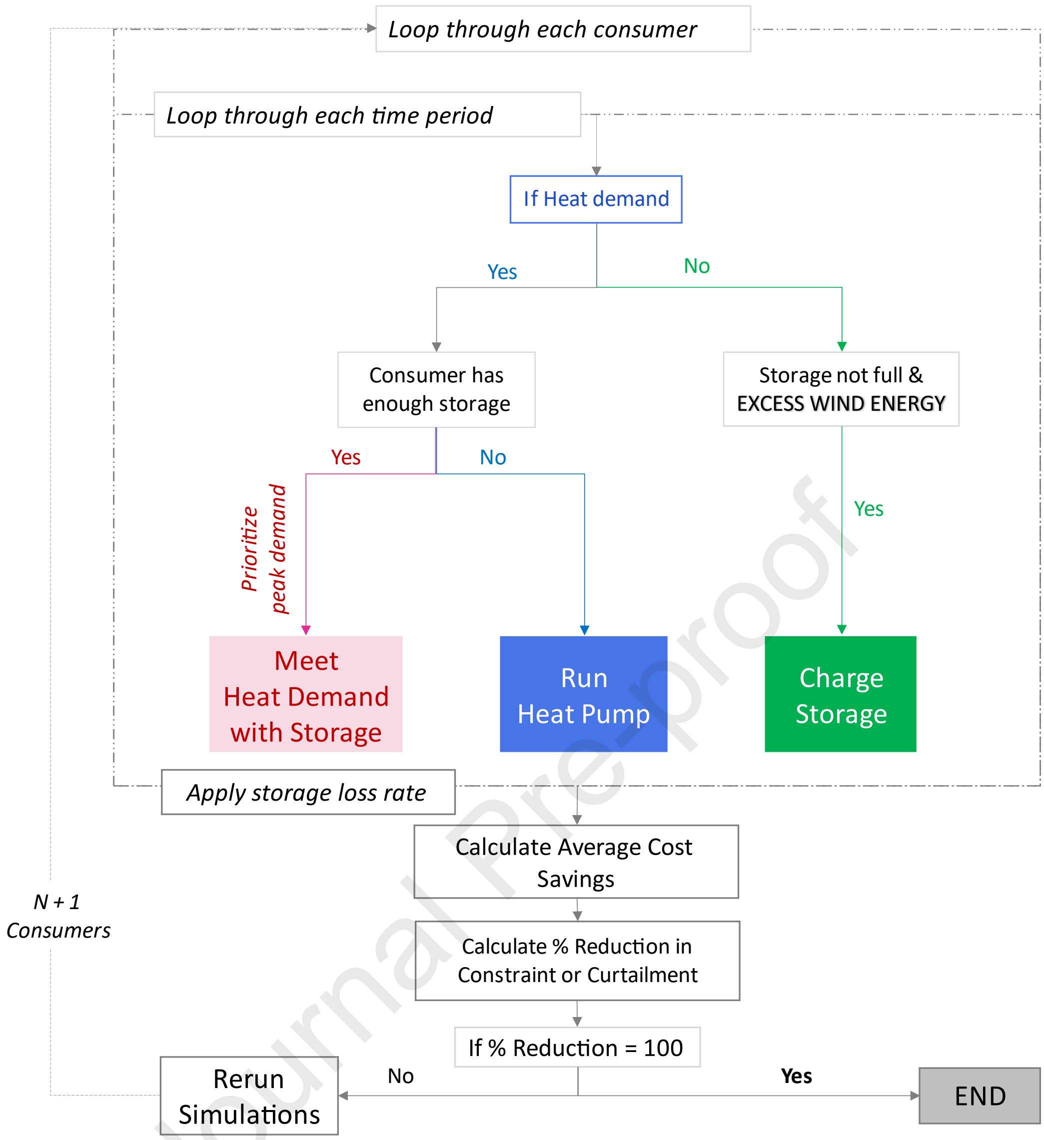

Fig. 5. Control Logic for the demand response simulation.

4.2. Distributing Excess Wind Energy

As the number of subscribers increases, there will be less free electricity for everyone, and hence the savings will be reduced. Furthermore, there might be other uses for excess wind energy. For example, the excess wind energy could be used for district heating schemes, stored in grid-scale batteries or used to produce green hydrogen for industrial use. Hence, it is important to derive the optimal number of subscribers that will produce an optimal reduction in excess wind energy as well as cost savings to the consumers. This can be formulated as an optimisation problem as given below.

$$\max_{y^S, y^R} \sum_{i=0}^{N} \rho_i{}^S \; y_i{}^S - \sum_{i=0}^{N} \rho_i{}^R \; y_i{}^R \tag{1}$$

$$\text{Subject to: } \sum_{i=0}^{N} y_i{}^R - \sum_{i=0}^{N} y_i{}^S = 0 \tag{2}$$

$$0 \leq \; y_i{}^R \; \leq i, \;\; \forall i \in \{1,2,3, \dots, N\} \tag{3}$$

$$0 \leq \; y_i{}^S \; \leq i, \forall i \in \{1,2,3, \dots, N\} \tag{4}$$

Where N is the total possible number of subscribers, ${\rho_i}^R$ is the percentage reduction in dispatch-down for *i* number of subscribers, ${\rho_i}^S$ is the percentage of energy cost saved for *i* amount of subscribers, y^R and y^S are the decision variables. The optimisation problem is solved using mixed-integer linear programming accounting for discrete number of subscribers and non-discrete excess wind energy.

In addition to deriving the optimal number of subscribers, two other scenarios are calculated:

- The number of social houses that can avail of the excess wind energy. Fuel Poor or Low-income consumer groups such as social housing could be prioritised in the excess wind energy dispatch process.
- The maximum number of households that could subscribe, given the limited amount of wind energy and the total number of households in a constraint group. This is important since depending on how future policy on utilisation of excess wind energy may turn out, the excess wind energy may be made available to everyone.

The maximum number of subscribers in each constraint group can be calculated using Eq. (5). This is the minimum between the total number of households in each constraint group, N_{CG} and the number of households that will ensure a 100% reduction in excess wind energy, $N_{100\%}$. The optimal number of subscribers is also limited by the total number of households in the constraint group.

$$Max\ No\ of\ Subscribers = Min\,\{N_{CG}\,, N_{100\%}\} \tag{5}$$

The total number of households and social housing in each constraint group was calculated using the Northern Ireland Demand Flexibility Map [55]. Simulations are performed for each of the constraint group and for curtailment. It is assumed that the consumer is on the Powershift tariff (A time of use tariff in Northern Ireland. It is currently preserved but has regulatory approval and is suitable for this kind of program). It is also assumed that the excess wind energy will be sold at the day-ahead market (DAM) rate (reflecting the value of constraint payment by the system operator) plus the supplier fee and that network charges are excluded since this service will benefit the network (lead to a higher load factor, reduce congestions, improve system voltage and overall system efficiency). The annual savings are calculated using a time-series of the DAM price for 2019 and compared with the scenario where the consumer is on a Powershift tariff but not managing excess wind energy (in this case the average consumer would have been paying £530 a year). The results of the simulations are presented in Section 5.

4.3. Power Flow Simulation

Further technical investigations are needed to ascertain how much demand can be accommodated in the existing distribution network without substantial reinforcement. Several factors will determine this capacity, such as the capacity of the primary and secondary substations and the location of the wind farms [57]. The Omagh case study network was modelled using the NEPLAN software [58]. The NEPLAN Web Service helps to integrate and import data from the demand response simulation model to the power flow calculation engine [59]. Fig. 6. shows the 33 kV and 11 kV network on NEPLAN. Measurement devices were placed at various points on the network to record the power flows. The time-series measurements were in 10 minutes resolution. Data for 2019 was considered. However, for the Omagh West substation, data for the month of February 2019 was corrupted. It was replaced with data for February 2018.

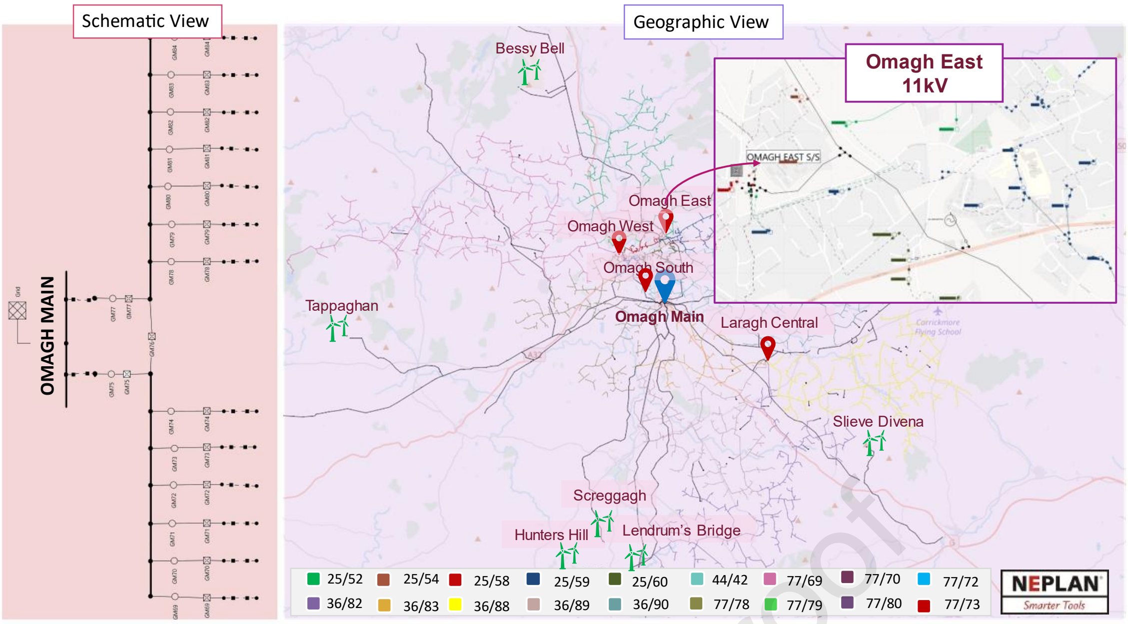

Fig. 6. Technical model of the Omagh network on NEPLAN software.

4.4. *Calculation of Heat Pump Hosting Capacity of the Distribution Network*

The hosting capacity is determined by calculating the maximum loading of the network. This is the maximum demand that can be accommodated on each network node before a loading or voltage violation occurs on any part of the system. The hosting capacity for each feeder and its secondary transformers is assessed. For each feeder f, the minimum between the number of residential consumers $N_{HH(f)}$ and the number of heat pumps that can be accommodated given the spare capacity of the network $N_{HPmax(f)}$ is chosen, as shown in Eq. (6). The maximum number of heat pumps $N_{HPmax(h)}$, that can be accommodated given the spare capacity of the feeder for an hour h is calculated using the difference between the feeder capacity F_C and the maximum feeder load recorded for that hour $F_{\max(h)}$, throughout the year. This is described by Eq. (7) and Eq. (8). Where C_{HP} is the electrical capacity of the heat pump, and d is the day of the year.

$$\forall f \in \{1, \dots, n_f\}, \qquad N_{HP(f)} = \min \{ N_{HH(f)} \,, \; N_{HPmax(f)} \} \tag{6}$$

$$\forall h \in \{1, \dots, 24\}, \qquad N_{HPmax(h)} = \frac{F_C - F_{\max(h)}}{C_{HP}} \tag{7}$$

$$F_{\max(h)} = \max_{1 \le d \le 365} \{ F_{d*h} \} \tag{8}$$

5. Results

5.1. *Impact of various number of subscribers to Wind Energy Constraint and Curtailment*

The results from Fig. 7 – 9 show that there is enough excess wind energy to serve the social houses in constraint group 1, 2 and 3. While tenants in constraint group 1 will save an average of £170 per year, tenants in constraint group 2 and 3 will save an average of £210 and £211, respectively. Demand turn-up from social houses could reduce wind energy constraint by up to 47% in constraint group 1, 11% in constraint group 2 and 10% in constraint group 3. There are enough subscribers to completely reduce the constraint in constraint group 1. However, in constraint group 2 and 3, there will still be left-over excess wind energy even if all households in the constraint groups were to subscribe. This means that residential demand flexibility is not enough to reduce the amount of excess wind energy in these constraint groups. Other opportunities such as the charging of electric vehicles or utilising the excess for producing green hydrogen should be investigated. The optimal and maximum number of subscribers in constraint group 3 equals the total number of households. This will produce a 66% reduction in excess wind energy with a savings of £147.

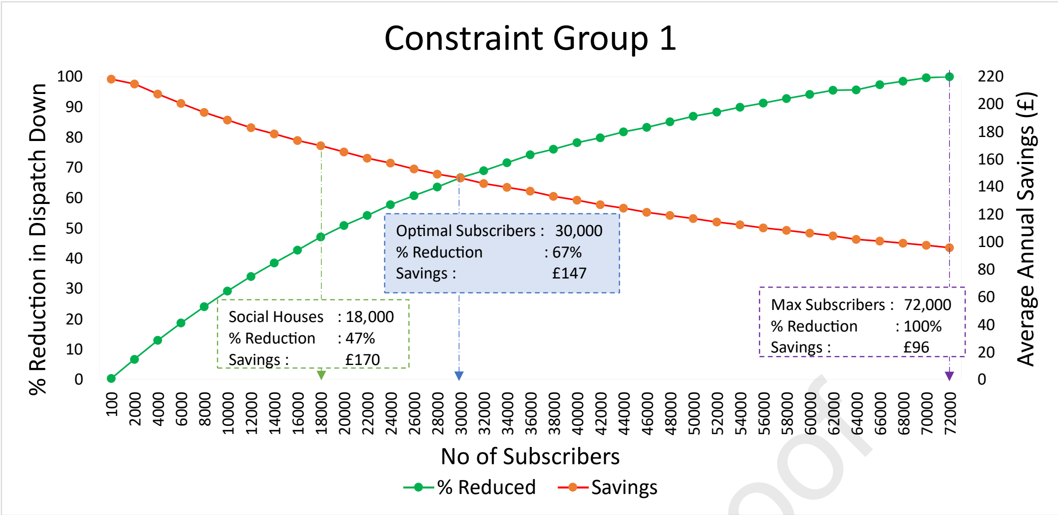

Fig. 7. Constraint Group 1: % wind energy reduction and cost savings vs number of subscribers.

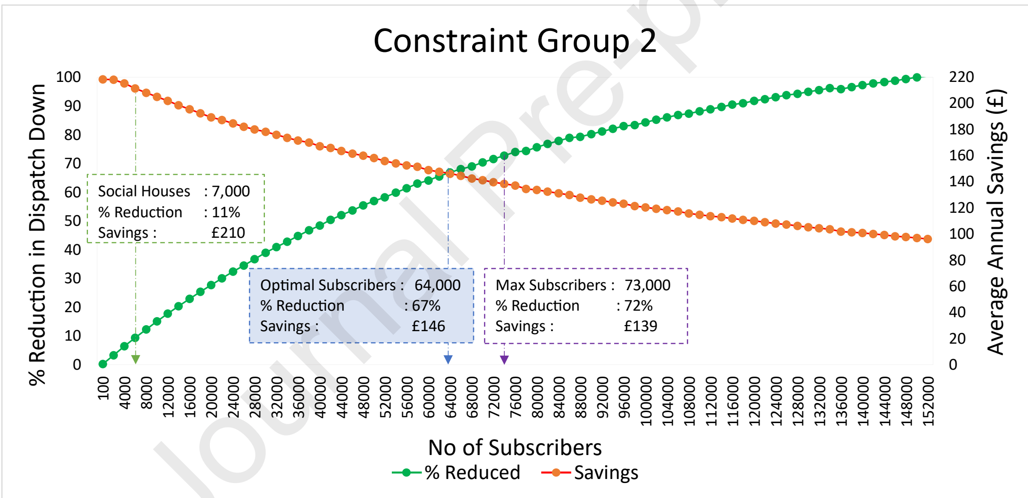

Fig. 8. Constraint Group 2: % wind energy reduction and cost savings vs number of subscribers.

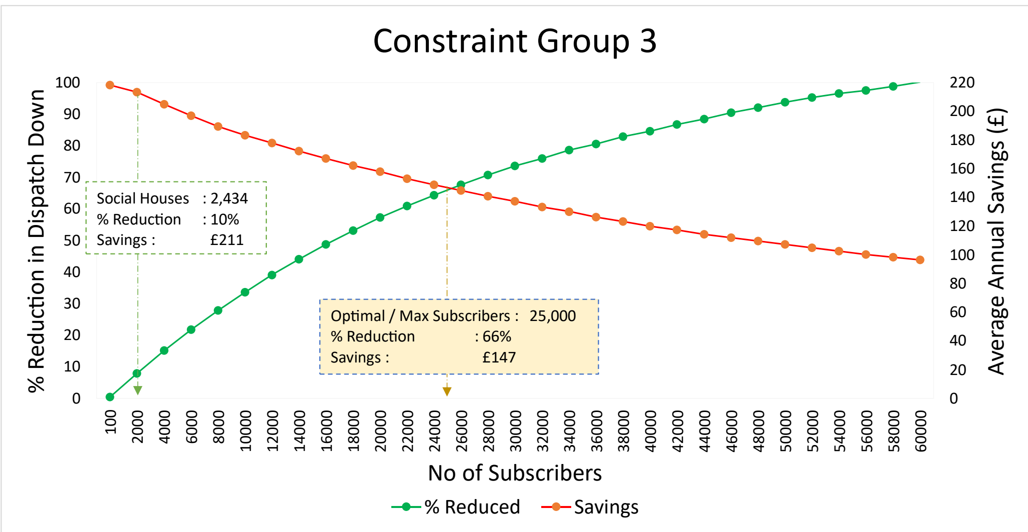

Fig. 9. Constraint Group 3: % wind energy reduction and cost savings vs number of subscribers.

As seen from Fig. 3, only about 2 GWh of wind energy was constrained in constraint group 4. In fact, this is solar energy constrained in the afternoon period. This can be considered negligible given the large number of households in constraint group 4. Fig. 10 shows the simulations for wind energy curtailment. As seen from the figure, even if curtailment opportunities are prioritised for social housing tenants in constraint group 4, the result still shows that they will have the lowest cost savings (£90). The optimal number of subscribers is 250,000; this will cause a 74% reduction in curtailment, with average savings of £73.

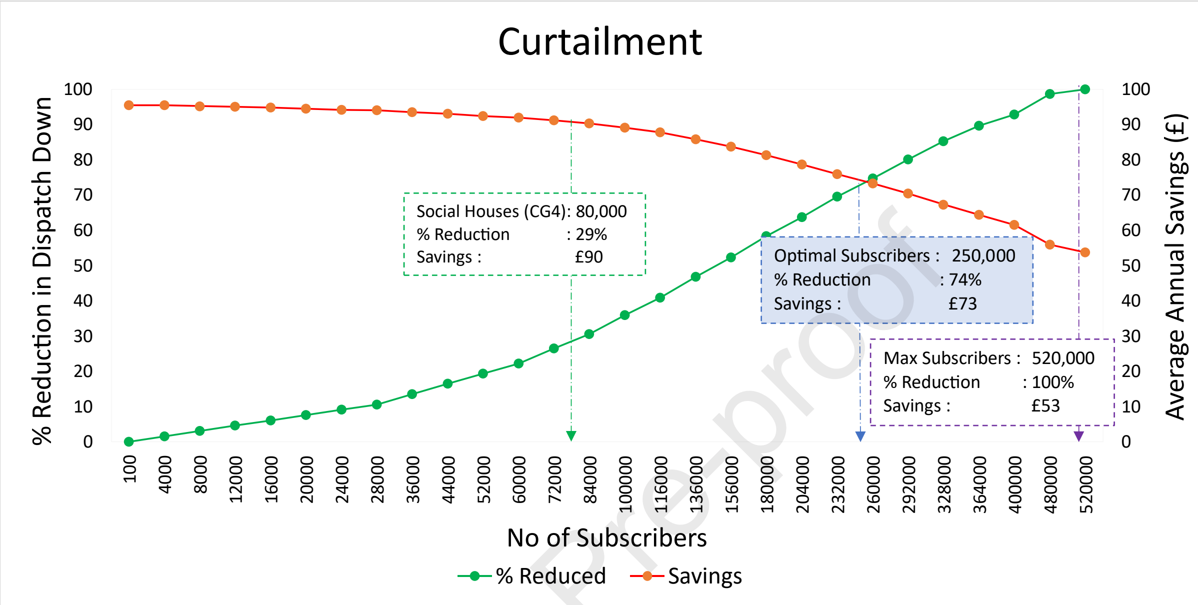

Fig. 10. Curtailment: % wind energy reduction and cost savings vs number of subscribers.

Curtailment is enough to serve all households in the excluded set of constraint group 4, since the maximum number of subscribers that will give a 100% reduction is 520,000 (99% of the total). Hence demand flexibility from residential consumers in constraint group 4 is enough to completely reduce wind energy curtailment in Northern Ireland. However, as mentioned earlier, there might be competing potential uses for excess wind energy; hence, the optimal number of subscribers could be targeted to maximise social impact/benefit.

5.2. Quantifying Benefits to Stakeholders

Using excess wind energy to provide low carbon heat will benefit all parties involved. The benefits to the various stakeholders are estimated in this section.

5.2.1. Consumers

Constraint and curtailments usually happen at periods with high wind penetration and low demand, which leads to a lower spot market price. Fig. 7-12 was computed using the Powershift tariff (a 3-price period time of use tariff). With this tariff, social housing tenants could save up to £220 (an average of £183) for providing constraint services and up to £100 (an average of £90) for providing curtailment services. The exact savings will depend on their constraint group and their priority in the dispatch process. If compared with a standard flat tariff, tenants will save an additional £103 a year. Hence the total savings when compared with a standard tariff would be an average of £286 for providing constraint services and £193 for providing curtailment services.

5.2.2. Wind Farms

As mentioned earlier, wind farms are paid constraint payments for the loss of market access. However, they are not compensated for curtailments. Wind farms are curtailed on a pro-rata basis. This scheme will reduce wind farm financial losses due to curtailments. The potential earnings are calculated using the time series of DAM price. Fig. 11 shows the monthly earnings for the various scenarios. This earning amasses to £2.1 million/year for the optimal scenario (using a time-series of DAM price and curtailment reduction from demand flexibility). A 10 MW wind farm would earn around an additional £19,400 annually. The study in [60] argues that wind farms should not receive 100% of the opportunity cost for constraint since reducing the income will send an important signal to the investor to select locations with sufficient network capacity, which would reduce the problem of constraint.

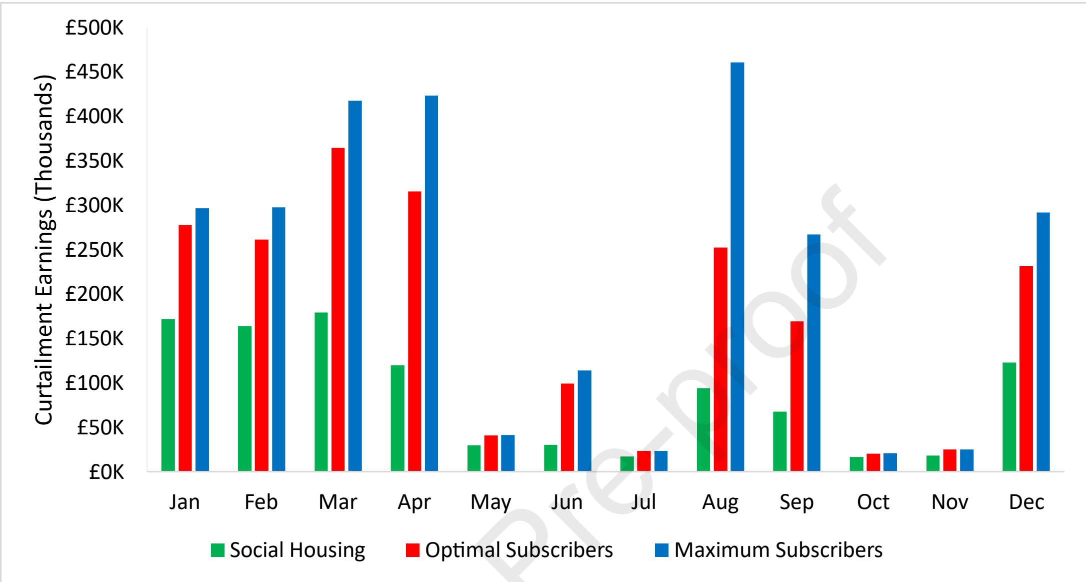

Fig. 11. Monthly curtailment payments to wind farms for the various scenarios.

5.2.3. System Operator

The benefit to the system operator includes a reduction in constraint payments. The simulation results show that 78% of constrained wind energy can be utilised if all houses in the constraint groups were to subscribe. This will save the system operator about £4.5 million per year in constraint payment (using a time-series of DAM price and constraint reduction from demand flexibility). The monthly savings are presented in Fig. 12. These savings will be further extended to all consumers in Northern Ireland, as they would not be charged for constrained energy not utilised by them.

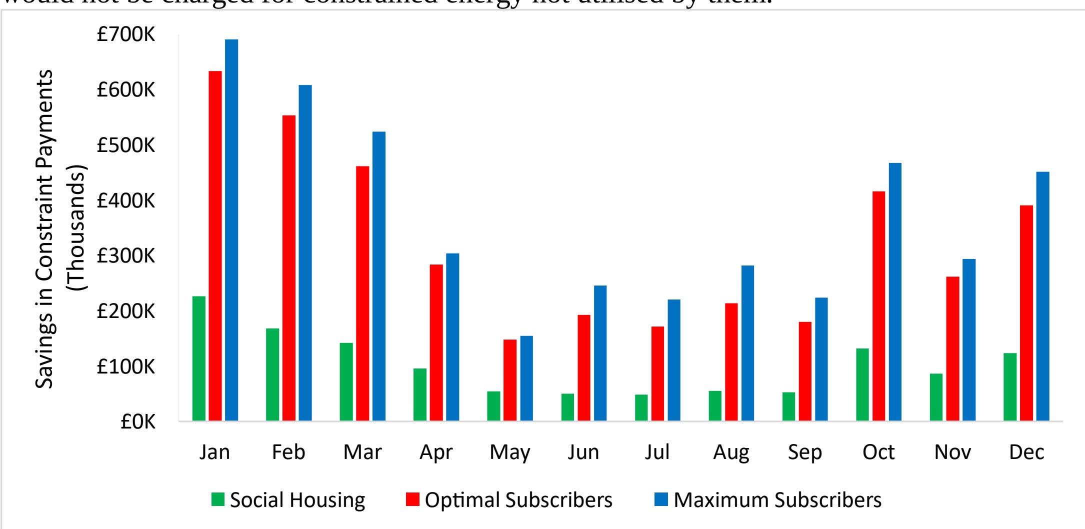

Fig. 12. Monthly savings in constraint payments for system operators for the various scenarios.

Table 1 shows a summary of the benefits to the various stakeholders.

Table 1. Summary of estimated benefits to various stakeholders

	Social Housing	Optimal Subscribers	Maximum Subscribers
Annual Constraint Payment	£1,236,100	£3,910,596	£4,471,654
Annual Constraint Payment / MW	£1,153	£3,648	£4,171
Constraint (No of Subscribers)	27,434	119,000	170,000
Annual Consumer Savings / Household	£183	£146	£121
Constraint (% Reduction)	20%	67%	78%
Annual Curtailment Payment	£1,030,051	£2,080,186	£2,678,427
Curtailment Payment / MW Wind Capacity	£961	£1,940	£2,499
Curtailment (No of Subscribers)	80,000	250,000	520,000
Average Consumer Savings / Yr	£90	£73	£53
Curtailment (% Reduction)	29%	73%	100%

5.2.4. Peak Demand Reduction and Aggregator Earnings

In addition to the benefits of reduced energy bills and other savings to the various stakeholders, there will be a reduction in average peak demand for the additional load during periods of congestion since the stored energy will meet some of the evening peaks [61]. Between 4 pm and 8 pm, there will be a 41% reduction in average peak demand for constraint and a 23.5% reduction in average peak demand for curtailment. For locations with congestion issues, an aggregator could bid this demand reduction to the local flexibility market and earn some revenue. For example, by providing sustained response between 4 pm – 8 pm on weekdays from the 1st of October to the 31st of March in the Northern Ireland local flexibility market [62], the aggregator could earn £65 a year per household for the constraint scenario and £24 a year per household for the curtailment scenario. Fig. 13 shows the annual hourly earnings for both scenarios.

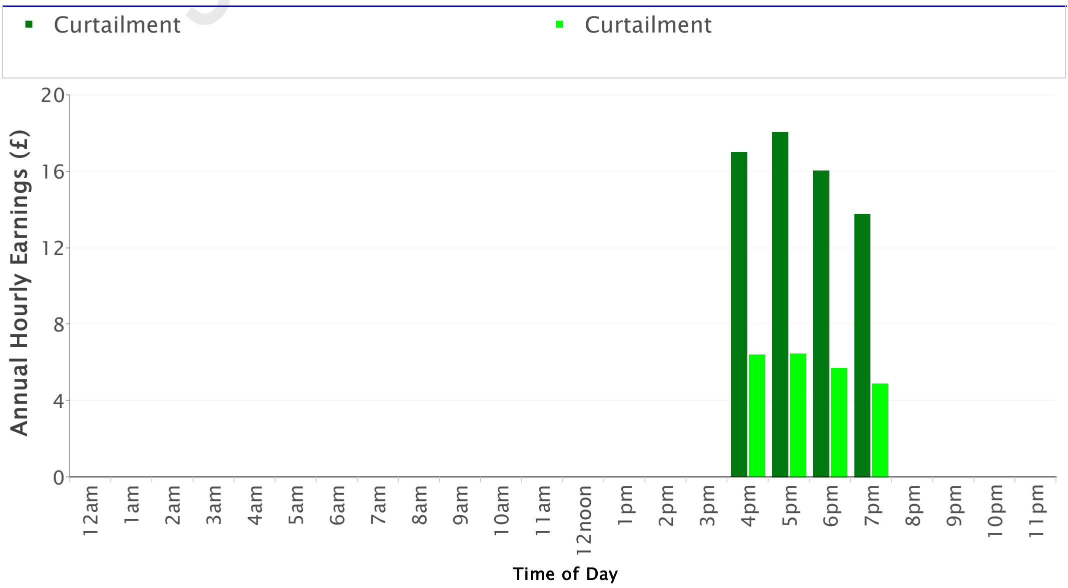

Fig. 13. Annual hourly earnings from congestion management service.

5.2.5. Reduction in CO_2 Emissions

Table 2 shows the CO_2 emissions for the various scenarios calculated using a time-series of the CO_2 intensity of the grid [63]. Switching from oil boilers to heat pumps will lead to a 46% reduction in CO_2 emissions. With the current grid CO_2 intensity there is no additional reduction in CO_2 emissions for the constraint and curtailment scenarios. However, with the use of flexible devices to balance the grid, there will be fewer fossil fuel generators running at periods of constraint and curtailments, hence there will be further reduction in CO_2 emissions for both scenarios.

Table 2. Annual CO_2 Emissions of an average consumer

	Oil	Default	Constraint	Curtailment
CO_2 Emissions (kg)	2270	1220	1258	1237
% Reduction		46%	45%	46%

5.3. *Impact on Distribution Networks*

This section presents the power flow results of the detailed case study network (Omagh BSP in Constraint Group 2). Fig. 14 shows the average hourly demand profile for some residential feeders. Clearly, the number of heat pumps that can be served by the network depends on the time of day. 4 am is the peak dispatch-down time as shown in Fig. 4, it is also the time with the minimum load. The number of heat pumps that can be accommodated at 4 am, and 6 pm is investigated since these periods represent the minimum and maximum loading on the network. From the load flow results, a maximum of about 10,000 heat pumps can be accommodated at 4 am. This is reduced to just 8,000 heat pumps at 6 pm. Fig.15 shows the distribution of the heat pump hosting capability across all residential feeders at 4 am and at 6 pm.

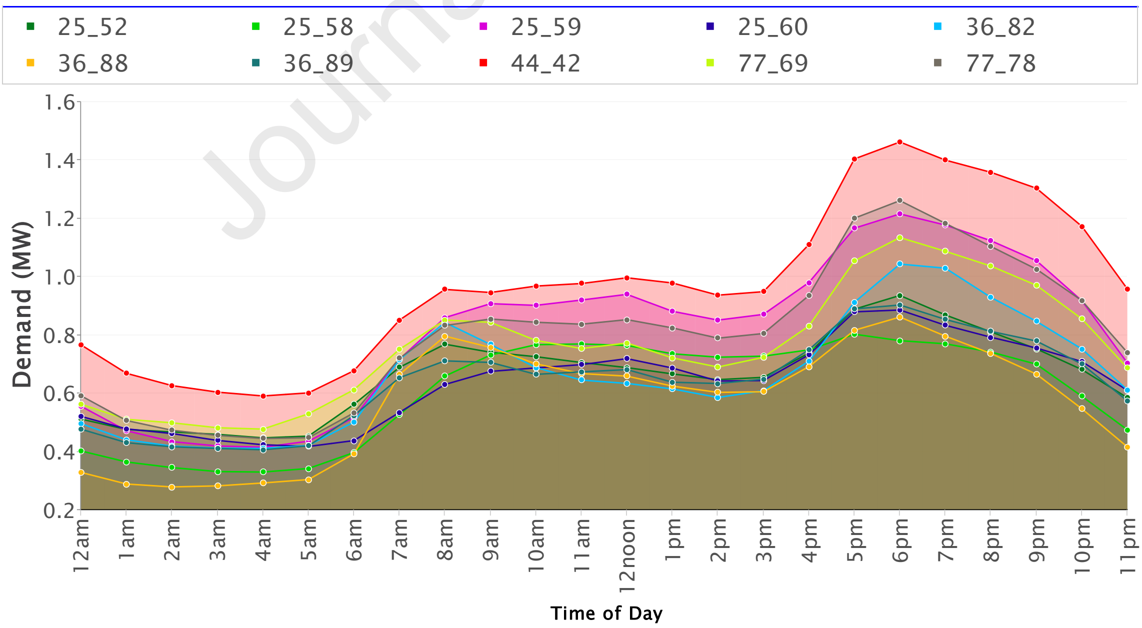

Fig. 14. Average hourly demand for some residential feeders.

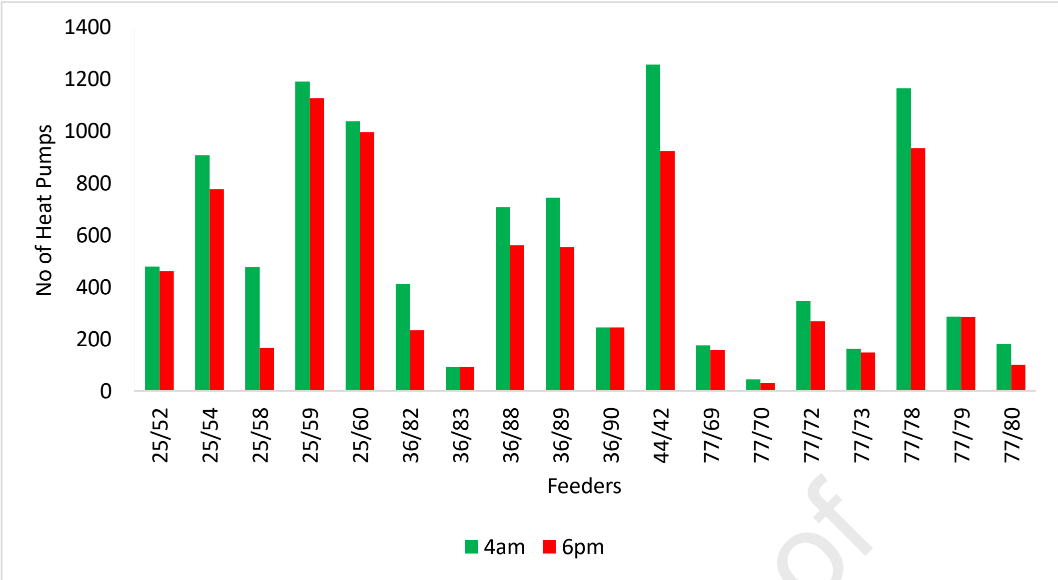

Fig. 15. Number of heat pumps that can be accommodated at 4 am and 6 pm.

Fig. 16 shows the voltage profiles of all residential feeders with maximum heat pumps connected. The loadings on very long feeders with consumers located greater than 10 km from the source node are severely limited by voltage constraints. This is particularly the case for Feeder 36/82.

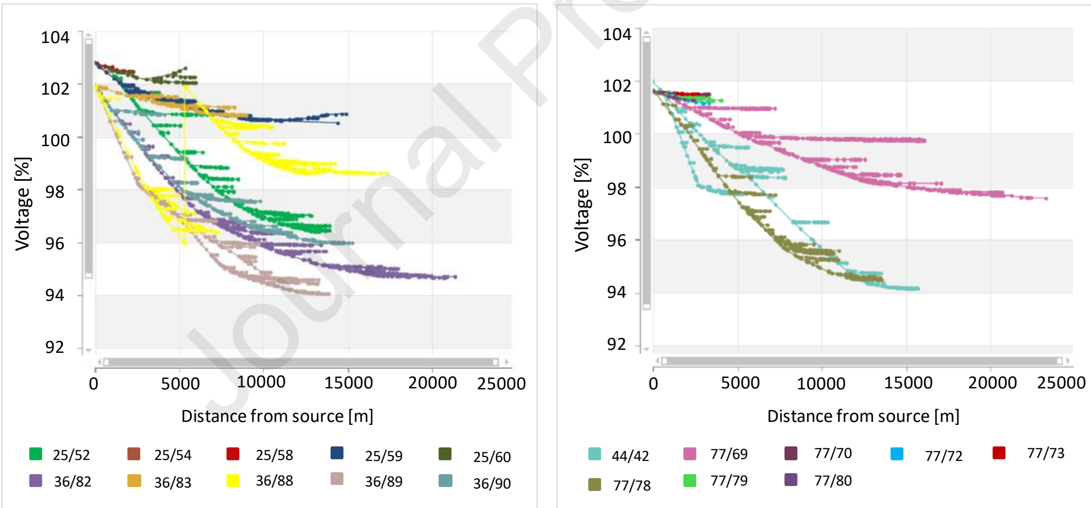

Fig. 16. Voltage profiles of the various feeders with maximum heat pump connected.

Fig. 17. shows the voltage violations on Feeder 36/82 at 4 am when 400 heat pumps are turned on. If these heat pumps are located randomly across the feeder, all 187 nodes located greater than 12 km from the source will have voltage less than 94% (Fig. 17a). The statutory voltage limit for 11 kV lines is 94% to 103% of the nominal value [64]. By locating these 400 heat pumps less than 10 km from the source nodes, all voltage violations are removed, as seen in Fig. 17b. Furthermore, the power losses on the feeder decrease from 0.088 MW in the random scenario to 0.072 MW when heat pumps are located near the beginning of the feeder.

However, discrimination on connecting heat pumps based on the distance from the feeder source is not acceptable, particularly since some of the fuel-poor consumers may be located at the far end of the feeders. To solve this problem, a voltage regulator can be installed on the feeder. For example, the voltage regulator placed at feeder 36/88 (Fig. 16) has improved the voltage profile for consumers connected greater than 5 km. This will allow more heat pumps to be connected since it would remove the voltage constraint issue.

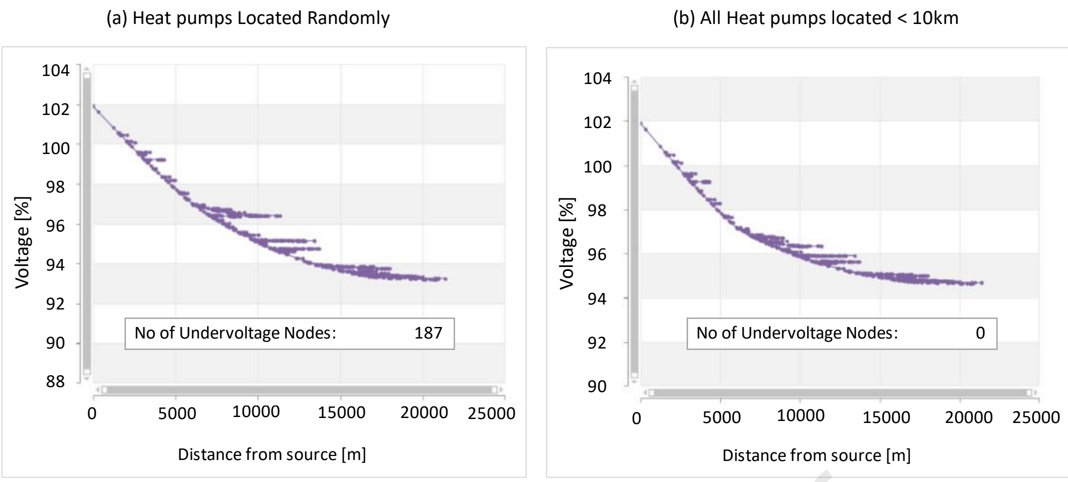

Fig. 17. Voltage profile of Feeder 36/82 (400 heat pumps at 4 am).

6. Conclusion

This paper investigates how excess wind energy can be used to provide low-cost heat to households. Managing the dispatch-down of excess wind energy will benefit all stakeholders in the energy system. Household management of curtailment and constraint are different services. While any consumer can help to manage wind energy curtailment wherever they are in the system, only consumers in a constraint group can alleviate constraint.

If all consumers were allowed to provide these services, there could be up to 78% reduction in constraint and a 100% reduction in curtailment. However, the amount of savings for an average consumer will reduce substantially to £121 for constraint services and £53 for curtailment services. Furthermore, there could be other competing uses for the excess wind energy, such as the production of green hydrogen for industrial use, grid-scale storage and district heating schemes.

An optimisation model is formulated to determine the optimal number of subscribers that will yield a sufficient reduction in excess wind energy while ensuring reasonable cost savings for the subscribers. The optimisation is performed for the various constraint groups and curtailment. The optimal number of subscribers for constraint is 95,000 and for curtailment is 225,000. This will yield a 67% reduction in constraint with an average cost savings of £146 and a 74% reduction in curtailment with an average cost savings of £73.

Wind farms will earn payments for curtailments. This amasses to £2.1 million for the optimal scenario and £2.7 million for the maximum scenario. System operators will save on constraint payments. This amasses to £3.9 million for the optimal scenario and £4.5 million for the maximum scenario. Furthermore, there will be a 46% reduction in CO_2 emissions when compared with the use of oil boilers for heating. Additionally, between 4 pm – 8 pm, there will be a 23.5% reduction in average peak demand when providing curtailment services and a 41% reduction in average peak demand when providing constraint services. An aggregator could bid this demand reduction to a local flexibility market and earn £65/year/household for constraint scenario and £24/year/household for curtailment scenario. Furthermore, making better use of indigenous wind energy reduces dependence on imported fossil fuel.

Other technical requirements need to be addressed in the distribution network before the mass adoption of low carbon electric heating. Mathematical formulations have been developed to determine the hosting capacity of distribution feeders and transformers. This is applied to a case study network. Households at the end of long feeder lines might experience voltage issues. Hence, network operators should investigate the consequence of mass adoption, install voltage regulators and perform other network investments necessary to facilitate the adoption of low carbon heat.

CRediT author contribution statement

Osaru Agbonaye: Conceptualization, Methodology, Validation, Formal Analysis, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Patrick Keatley:** Conceptualization, Data Curation, Writing – Review & Editing, Supervision. **Ye Huang:** Conceptualization, Writing – Review & Editing, Supervision. **Osasere F. Odiase:** Writing – Review & Editing. **Neil Hewitt:** Conceptualization, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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- A framework for utilizing wasted wind energy for heating homes is investigated.
- Currently wasted wind energy could save fuel poor households up to £220 per year.
- A 10MW wind farm could earn about £20,000 annually from avoided curtailment.
- System Operators could save up to 78% on constraint payments.
- Mathematical model to determine heat pump hosting capacity of a grid is developed.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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