IMPERIAL

HeatNet Alpha

Deliverable 4.1.1

Review of Alternative Approaches

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WP 4: Whole system benefits

Potential benefits of coordinated HP control on whole system investment and operation

Task 4.1 Analysis of system configurations
- Analysis of the peak demand contributions and maximum diversity factors from heat pump (HP) system configurations, both with and without HeatNet.

Task 4.2 Analysis of voltage-driven reinforcement
- Analysis of the reductions to voltage-driven reinforcement from using HeatNet across the three LV use cases and scaled for the UKPN and GB networks

Task 4.3 Review of alternative approaches
- Review and development of alternative approaches for integrating HeatNet technologies into distribution network planning

D4.1.1 Review of alternative approaches (week 25; 17 Feb)

Task 4.4 Summary of the whole-system benefits
- Evaluation of the whole-system benefits of applying HeatNet, looking at competition with other flexibility technologies like demand response and battery storage.

Task 4.5 Whole-system evaluation of HeatNet
- Development of a cross-cutting report analysing the impact of the HeatNet method on the UKPN's distribution network and across the GB energy system under different future scenarios

D4.2.1 Whole System Evaluation of HeatNet (week 29; 17 Mar)

Task 4.1 Analysis of system configurations

Analysis of the peak demand contributions and maximum diversity factors from heat pump (HP) system configurations, both with and without HeatNet

Data Gap Analysis
Source: Passiv analysis during HeatNet discovery phase

Baseline annual half-hourly load profiles based on

- Normalised profile shapes
  - Four profile classes
  - 18 characteristic days
- Different peak demand

Heat pump annual half-hourly load profiles

- 20 archetype profiles
  - Four different HP nameplate rating 1.7, 2.7, 4 and 4.6 kWe
- Allocated to 172 domestic customers, repeating 8-9 times heat pump archetypes
  - Total installed HP nameplate rating is 479.2 kWe (=68*1.7+44*2.7+52*4+8*4.6)
  - Average HP nameplate rating is 2.786 kWe (=479.2/172)

Considered HP control strategies without negative impact on customer comfort levels

- Manufacturer control (counterfactual)
- Passiv control where heat pumps are controlled to increase heat pumps efficiency
- HeatNet where heat pumps are controlled to minimise impact of voltage drop

Annual Peak Diversity

Coincidence factor: ratio of simultaneous peak of group of electrical appliances or consumers to sum of their individual peaks (≤ 1). Typically reducing in value by number of appliances or consumers reaching saturated value for ‘infinite’ number of appliances or consumers.

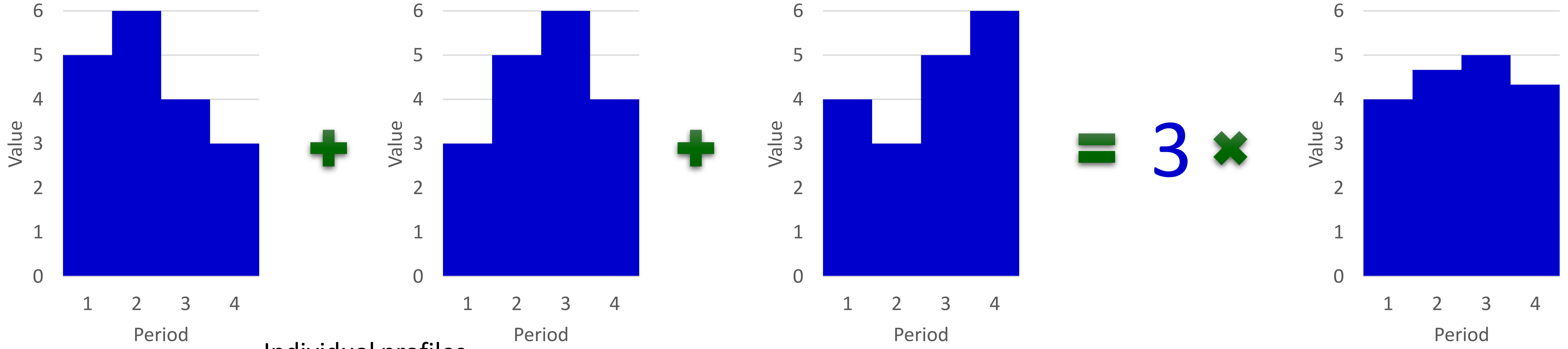
Diversity factor: reciprocal of coincidence factor (≥ 1)

In distribution network planning analyses, annual factors are used, including **After Diversity Maximum Demand** (ADMD)

Illustration

- Sum of individual peaks is 6+6+6=18 and simultaneous peak is 3x5=15, and ADMD is 5
- Coincidence factor is 15/18=0.83 and diversity factor is 18/15=1.2

Diversified profile



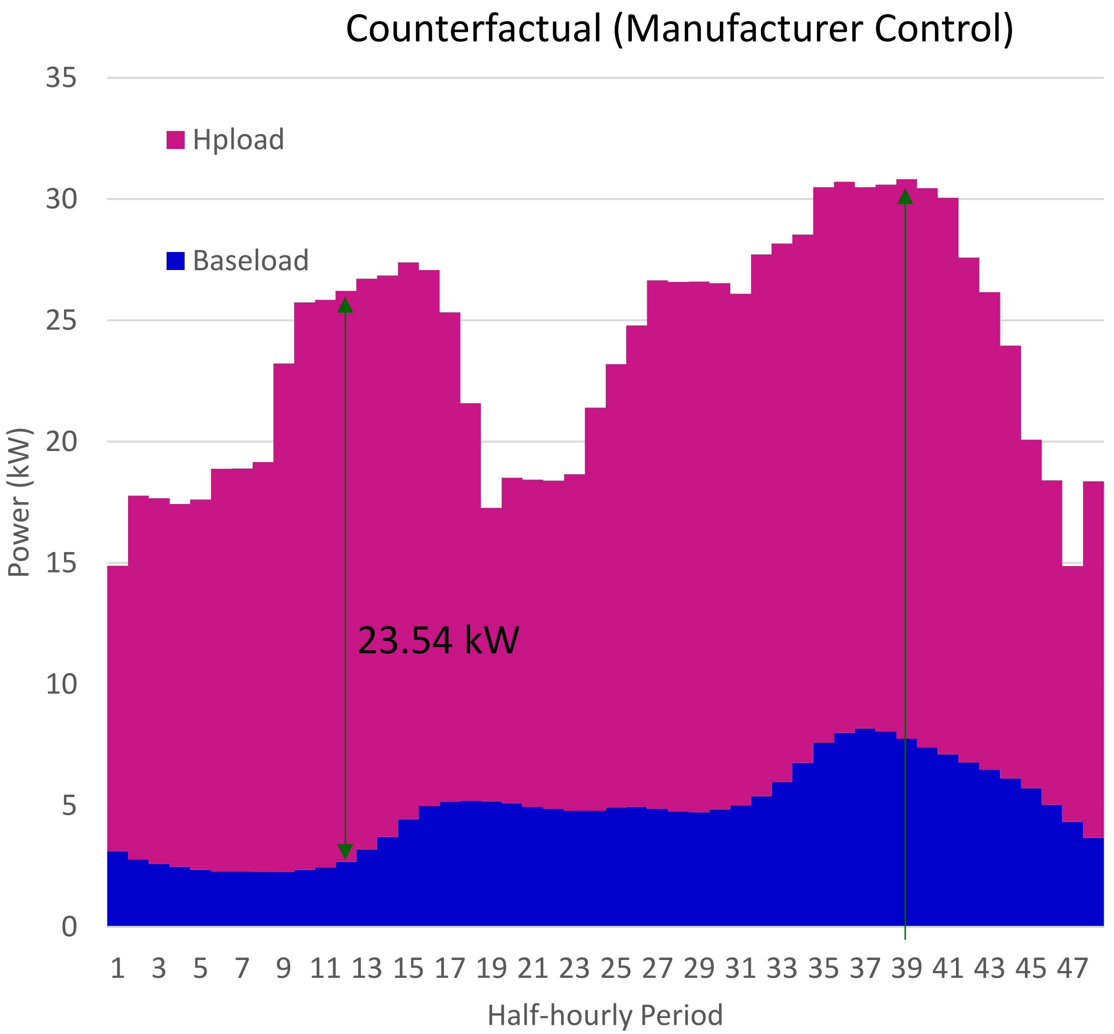
Individual profiles

Coincidence Factor Calculation Algorithm

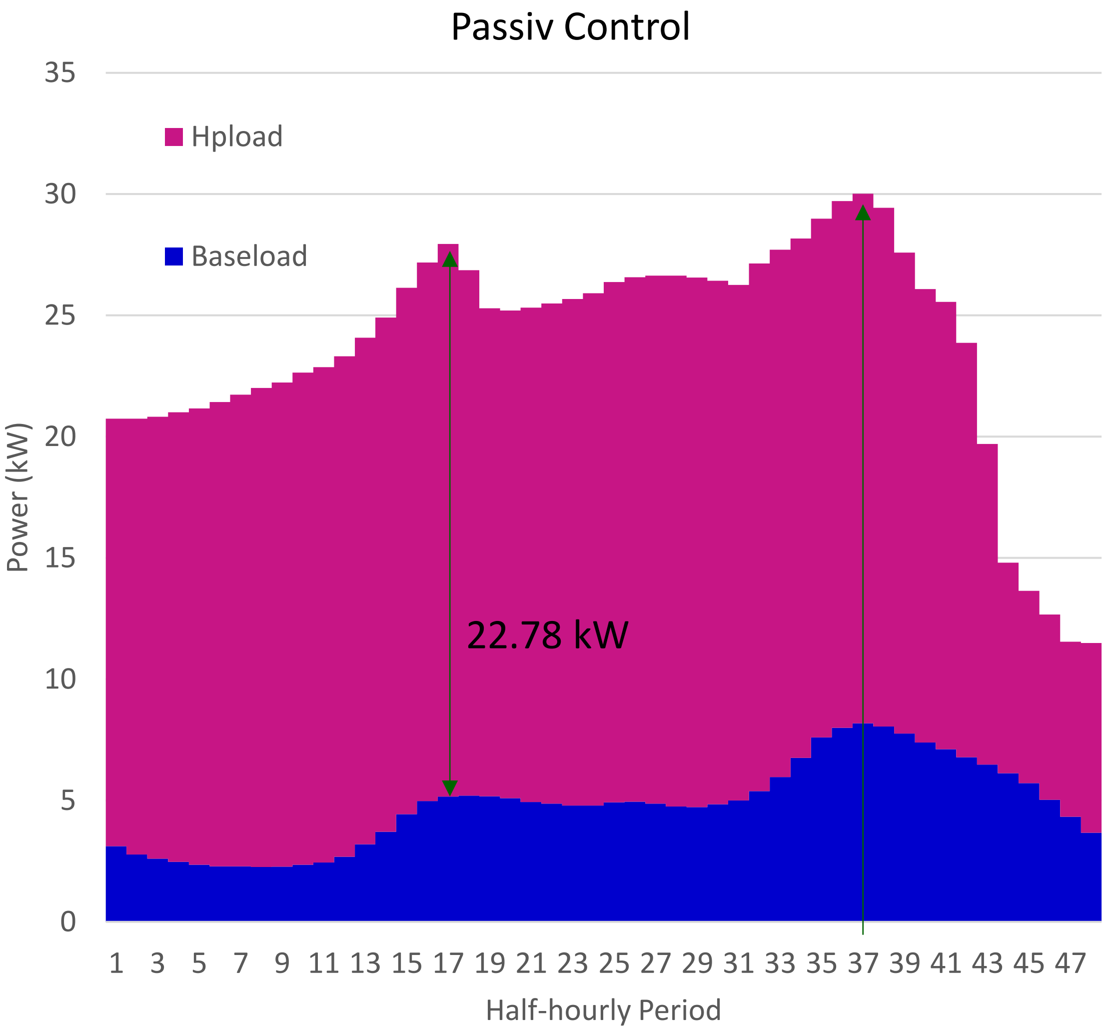
Monte Carlo Approach

- For desired number of customers/heat pumps, randomly select domestic customers
- For selected customers
  - Sum baseline profiles to obtain summary baseline annual profile
  - Sum HP profiles to obtain summary HP annual profile
  - Sum summary and HP annual profiles to obtain total annual profile
  - Sum HP electrical ratings to obtain total HP electrical rating
- Find total peak and binding period when total peak occurs
- For binding period find contribution of HP to total peak
- Divide contribution of HP to total peak with total HP electrical rating to obtain coincidence factor
- Repeat above 200 times to obtain statistics of coincidence factor
- Repeat above for different desired number of customers/heat pumps to obtain relationship between number of HPs and coincidence factor
- Repeat above for two simulated controls of HPs
- Repeat above for HP profiles only i.e. excluding baseline profiles

Example – Ten Customers and HPs – Electrical Power for Peak Day, 28 Feb

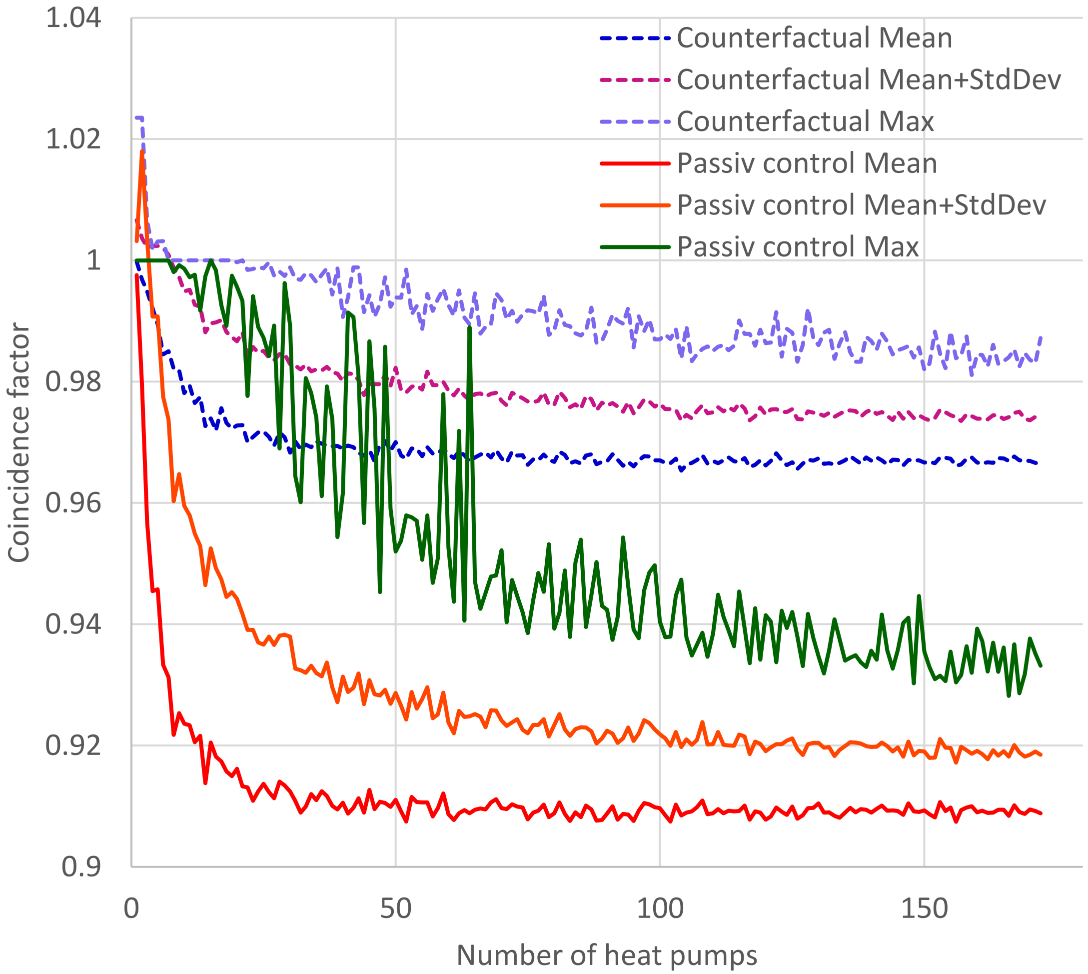


Peak 30.83 (=7.77+23.06) kW @ 19-19.30
Coincidence factor 0.977 (=23.06/23.6)
HP consumption 454.1 kWh, LF=80.2%



Peak 30.02 (=8.18+21.84) kW @ 18-18.30
Coincidence factor 0.925 (=21.84/23.6)
HP consumption 456.8 kWh (100.6%), LF=80.6%

Domestic Heat Pump Coincidence Factors
Monte Carlo calculation



Obtained Relatively high value for HP coincidence factors

- If homeowner installs higher rated HP, coincidence factor would be lower

Coincidence factors

Counterfactual

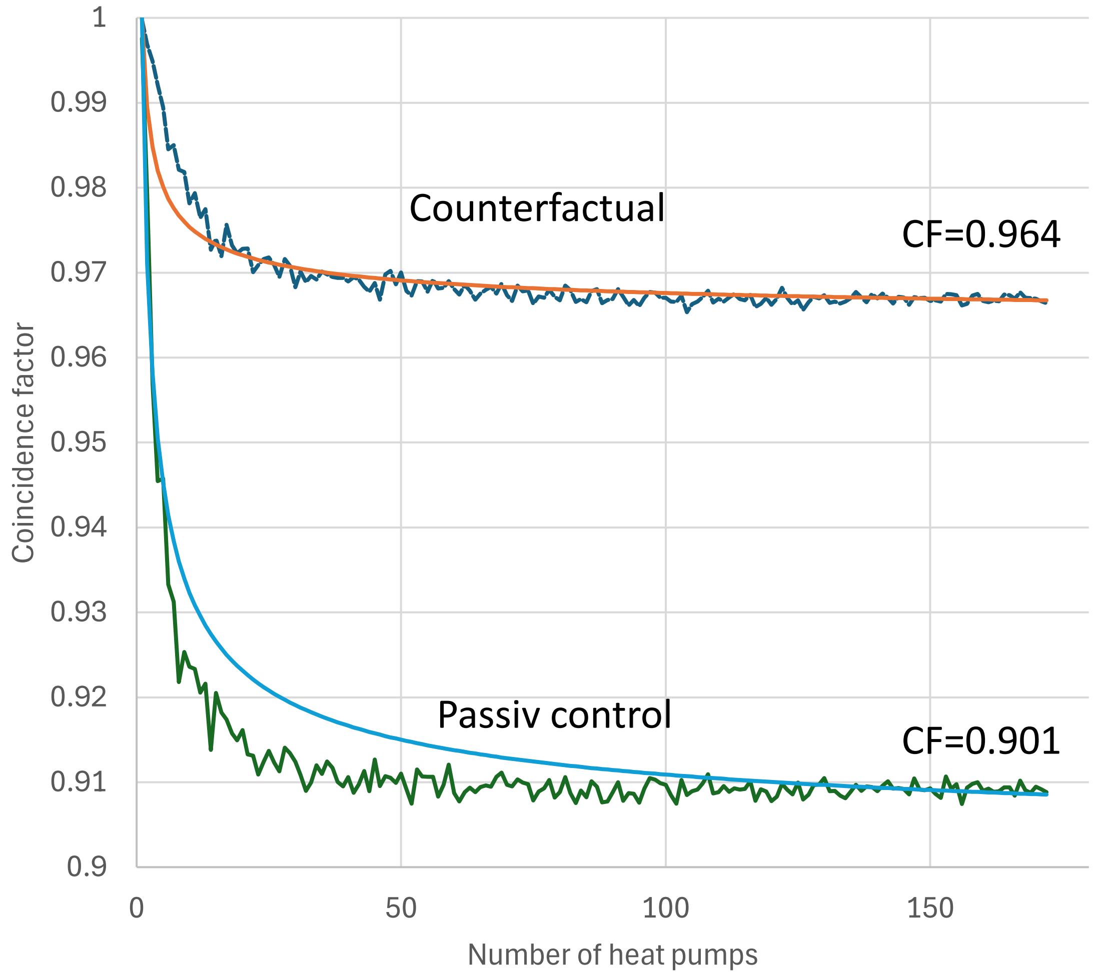
- Maximum value starts from value greater than one as occasionally for some heat pumps electrical power is greater than rated power and subsequently reduces linearly from 1 towards 0.98 as number of heat pumps increases
- Mean (average) value starts from 1 for one heat pump and reduces fast to about 0.97 for 20-ish heat pumps. Subsequently reduction is slow to about 0.966 for 172 heat pumps

Passiv control

- Observed high variability of maximum value starting from 1 and reducing towards 0.93 for 172 heat pumps. Potentially higher number of Monte Carlo samples could reduce variability.
- Mean (average) value starts from 1 and for 12 heat pumps reaches 0.92 and for about 40 heat pumps reaches 0.91 after which value is practically saturated
- HeatNet control of heat pumps reduces use of heat pumps during peak condition and hence coincidence factor is lower

Mathematical Equation of Domestic Heat Pump Coincidence Factors

Interpolation of observed coincidence factors with mathematical equation



Rusck's equation for coincidence factor

$$CF_n = CF + \frac{1 - CF}{\sqrt{n}}$$

where CF is coincidence factor for infinite number of similar electrical appliances or customers, and n is number of similar electrical appliances or customers

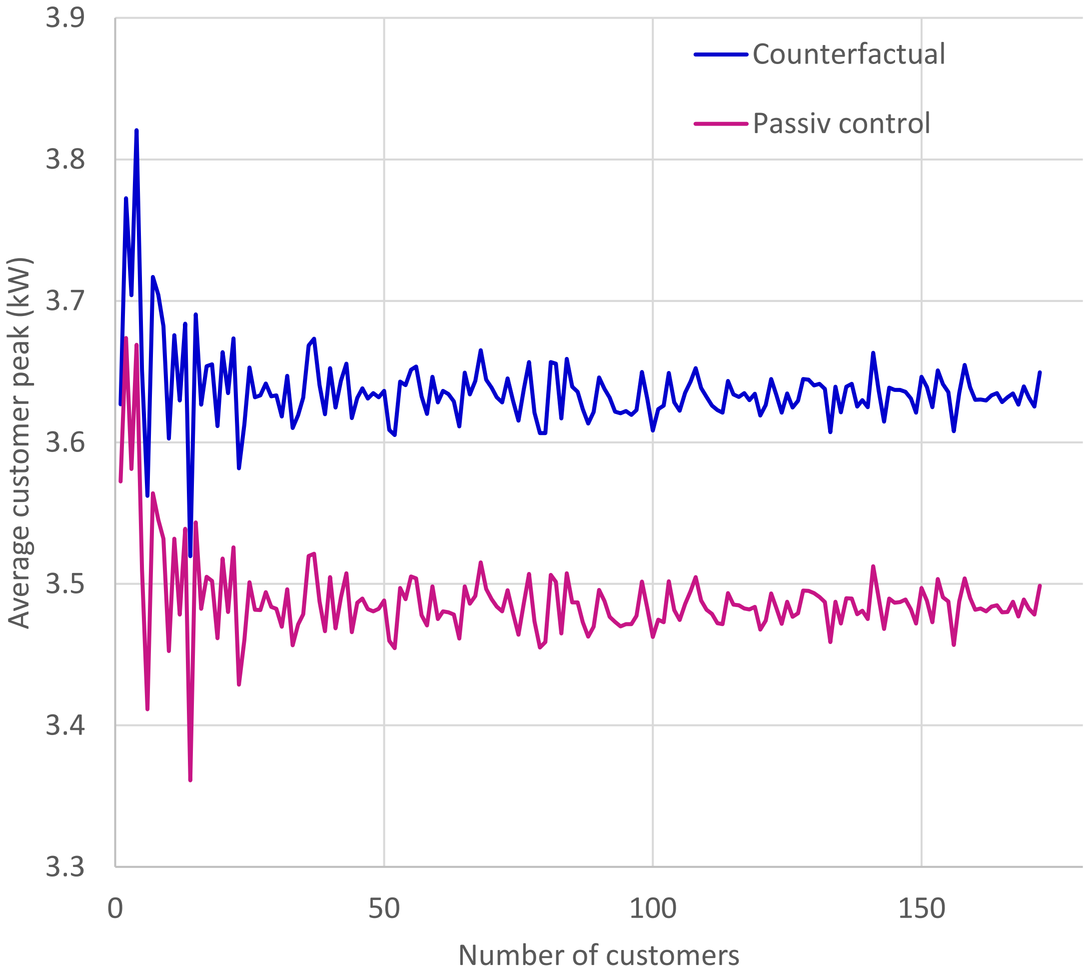
Maximum peak, P_n^{max}, of n similar electrical appliances or customers is

$$P_n^{max} = CF_n \cdot n \cdot P_1^{max}$$

where P_1^{max} is maximum peak single electrical appliance or customer, $P_1^{max} = \overline{P_1} + k \cdot \sigma_1$, where $\overline{P_1}$ is average peak and σ_1 is standard deviation of single electrical appliance or customer, and k is desired confidence level constant

Reference: S. Rusck, "The simultaneous demand in distribution network supplying domestic consumers," ESEA Journal, vol. 10, pp. 59–61, 1956.

Average Peak of Domestic Customer with Heat Pump

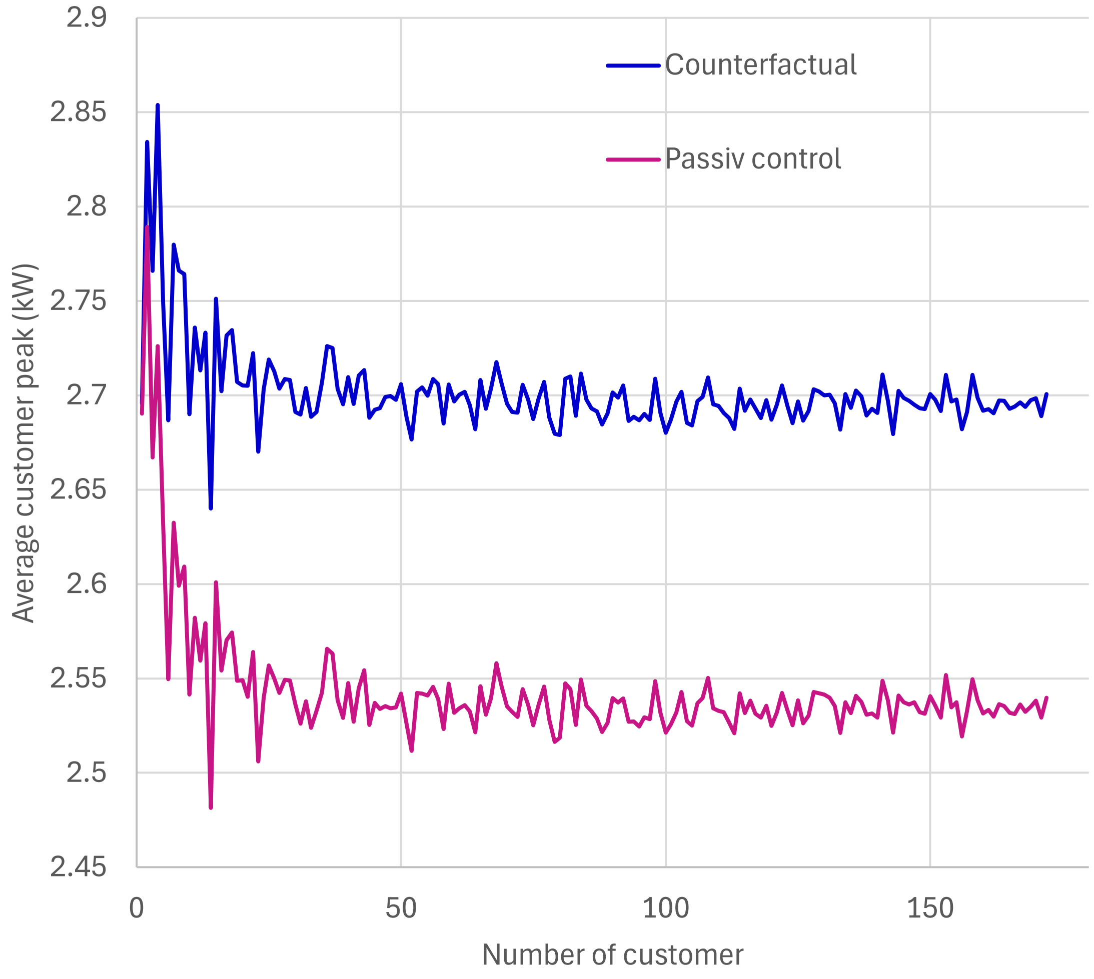


Typically, with increased numbers of customers the overall peak reduces with saturation value reached between 20-30 domestic customers

Average customer peak, for more than 40 customers is about

- In counterfactual 3.63 kW per customer
- In Passiv control 3.48 kW per customer
- Observed average customer peak reduction of about 4.1%

Average Peak of Heat Pump



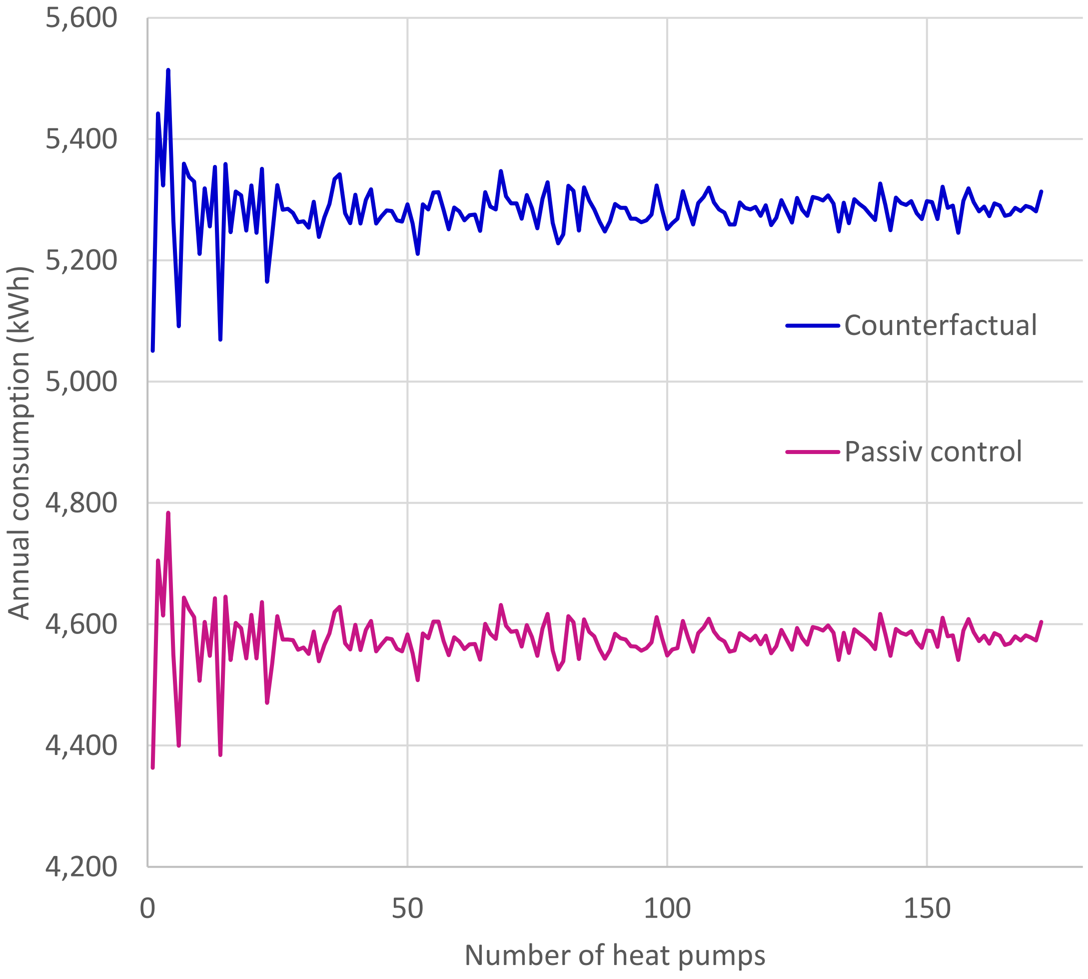
Typically, with increased numbers of customers the overall peak reduces with saturation value reached between 20-30 heat pumps

Average customer peak, for more than 40 heat pumps is about

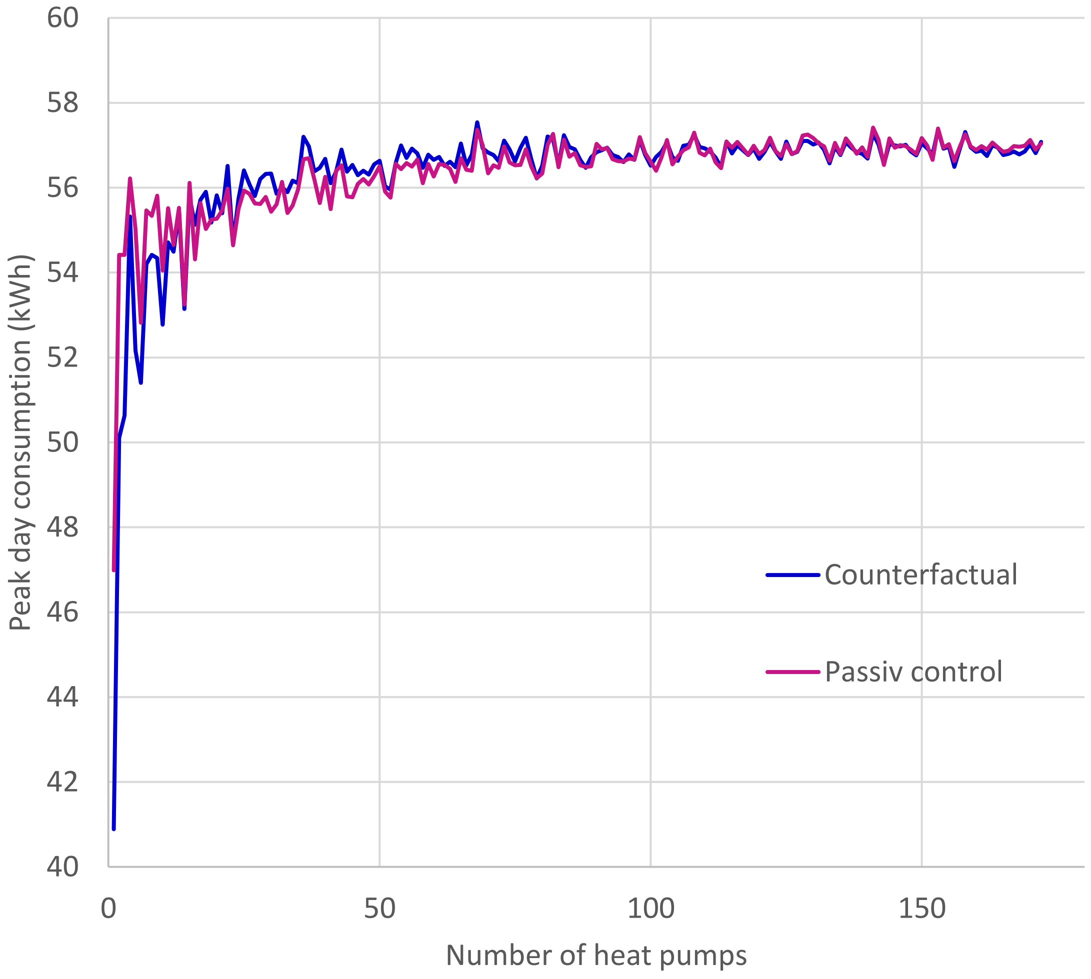
- In counterfactual 2.70 kW per customer
- In Passiv control 2.53 kW per customer
- Observed average customer peak reduction of about 6.0%

Average Heat Pump Energy Consumption

Passiv control reduces average annual consumption of heat pumps for about 13.5%.



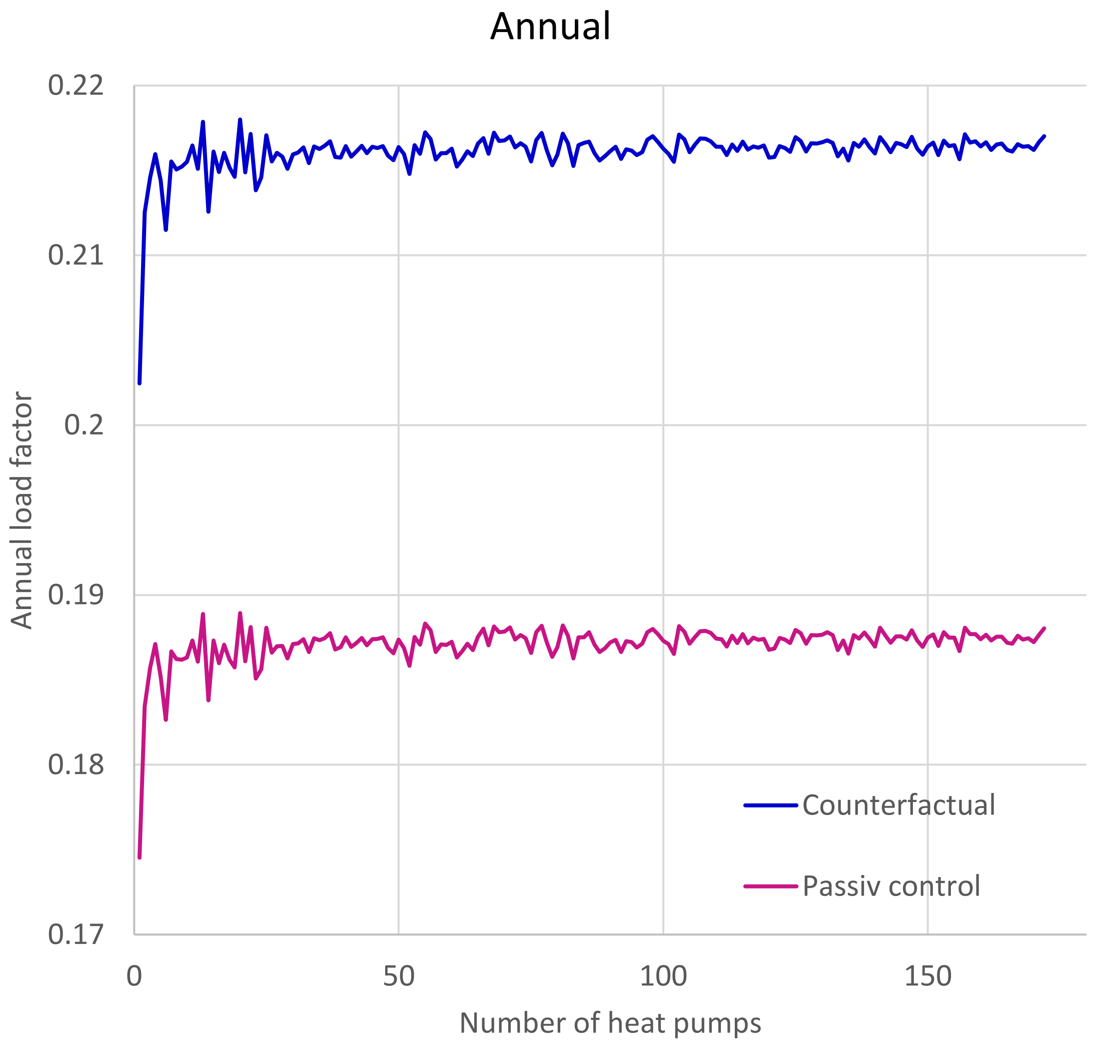
For fewer heat pumps, it is observed that Passiv control increases average daily consumption of heat pumps but for greater number of heat pumps daily consumption is similar as in Counterfactual.

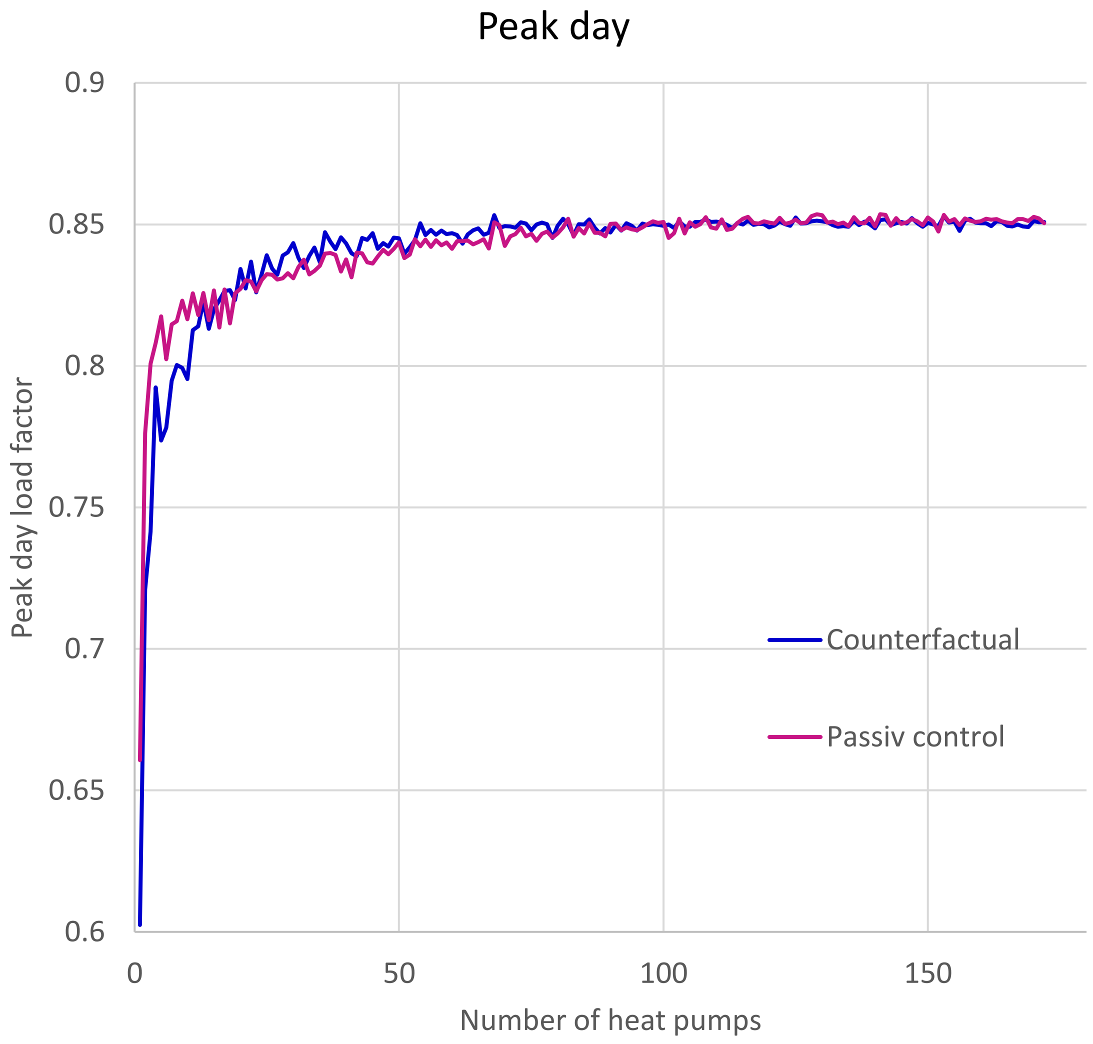


Average Heat Pump Load Factor

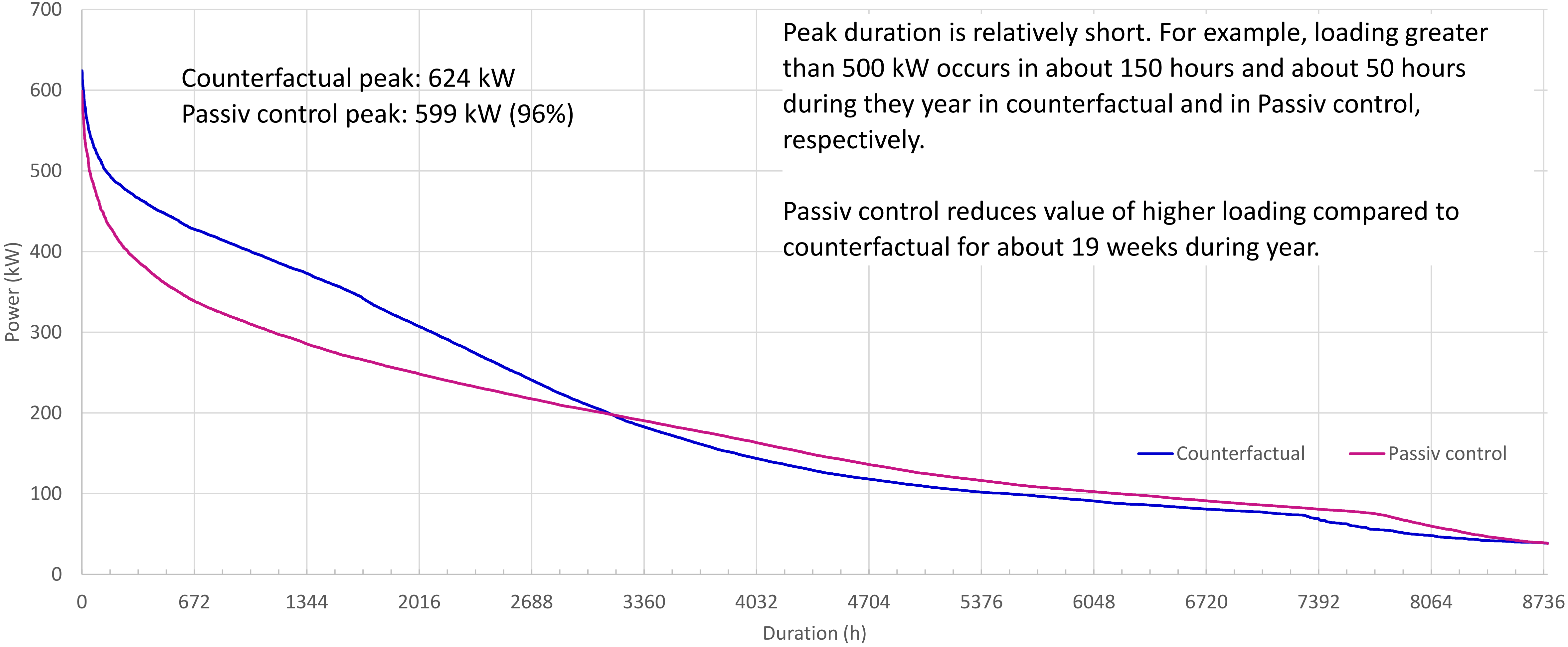
Load Factor values follows consumption trend

Heat pump peak day load factor, as expected, is significantly greater than annual load factor and for about 70 heat pumps saturates to about 85%.





Domestic Customers Load Duration Curves
Sum of all domestic baseload and heat pump load



Key observations

Passiv control reduces peak and from about 40 customers reduction is relatively constant at about 4.1%

- Load of domestic non-hybrid HP is reduced for about 6%

Passiv control reduces annual heat pump consumption for about 13.5%

- Peak day consumption from about 70 heat pumps is relatively same in both Counterfactual and Passiv control scenarios
- Annual and peak day load factors follow similar trends

Reduction in domestic peak duration and reduction in higher power lasts for about 19 weeks during year in Passiv control

Annual coincidence factor is relatively high and greater than 0.9 in Passiv control and 0.96 in counterfactual

- Coincidence factor of n HPs could be approximated by Rusck's equation, $CF_n = CF + \frac{1-CF}{\sqrt{n}}$, using value for CF
  - Counterfactual: 0.964
  - Passiv control: 0.901

Task 4.2 Analysis of voltage-driven reinforcement

Analysis of the reductions to voltage-driven reinforcement from using HeatNet across the three LV use cases and scaled for the UKPN and GB networks

Data Gap Analysis
Source: Passiv analysis during HeatNet discovery phase

The following data are provided assuming best possible heat pumps allocation to 152 homes (181 total customers of which are 172 homes)

- Uncoordinated half-hourly power and voltage drop profiles for each customer location and considered period during the analysed time horizon (whole of 2018)
- Coordinated half-hourly power and voltage drop profiles for each customer location and two-day period (28 Feb – 1 Mar 2018) during the maximum demand

Voltage Drop Analysis

Analysis is conducted per considered network feeder and summarised in the following table

Feeder index	Feeder length (m)	Customers count	Homes count	HPs count	Coutnerfactual peak (kW)	HeatNet Peak (kW)	Counterfactual max voltage drop (V)	HeatNet max voltage drop (V)	Peak reduction (%)	Voltage drop reduction (%)
1	524.47	32	31	31	103.41	103.86	4.677	4.685	-0.44	-0.17
2	1724.78	84	78	58	247.53	218.77	16.477	13.799	11.62	16.25
3	64.9	1	1	1	5.82	5.82	0.046	0.046	3.72	7.73E-04
4	784.07	64	62	62	213.93	187.95	15.797	13.797	12.15	12.66
Transformer	**3098.22**	**181**	**172**	**152**	**570.68**	**499.96**	**16.477**	**13.799**	**12.39**	**16.25**

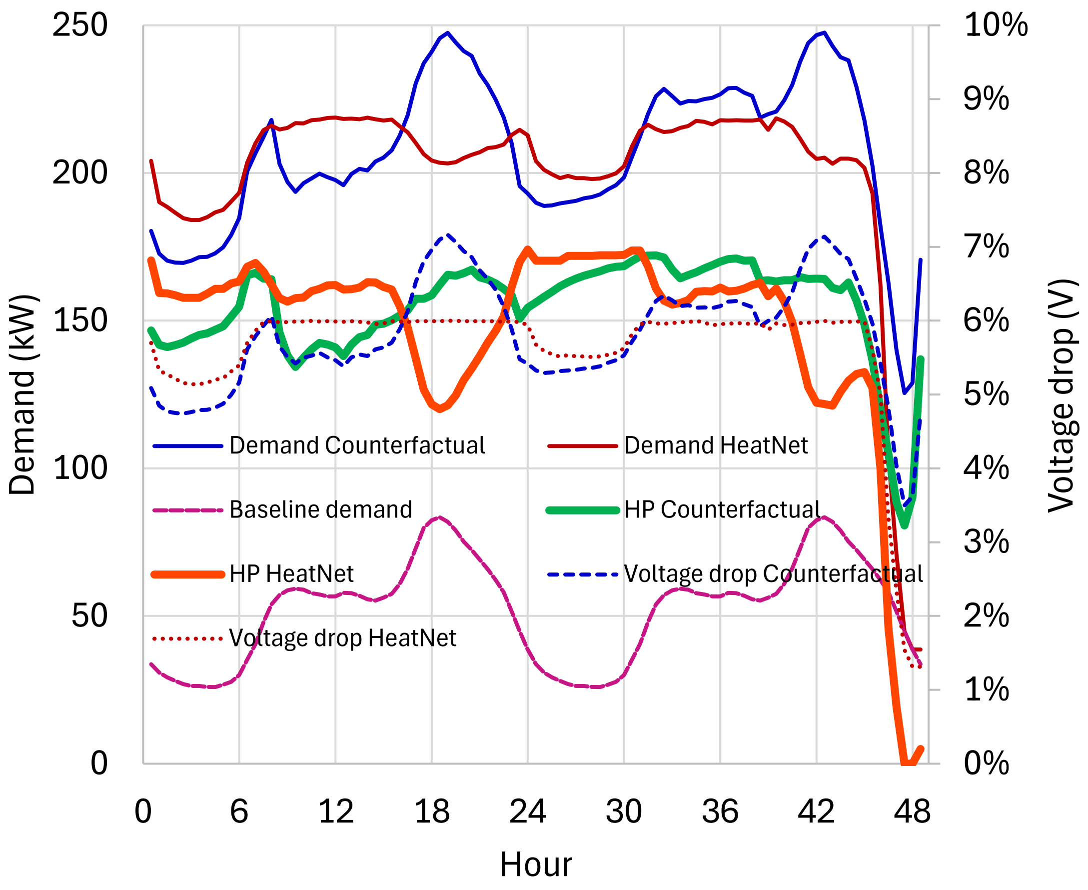
Analysed distribution LV network consists of four feeders ranging from 65 m to 1.7 km in length. Total LV network length is about 3.1 km.

Feeder peaks are not coincidental, and transformer peak is lower than the sum of feeder peaks albeit negligible in Passiv control case. In HeatNet case, transformer peak is lower for about 3.2% due to diversity.

For feeders 2 and 4, where network congestion is observed, improvement in voltage drop is between 12.7-16.3% and in peak reduction is between 11.6-12.1%

- All homes supplied from feeder 4 have HP installed and potentially HeatNet could have capability to mitigate voltage drop even further, as there is no incentive for the HeatNet to further reduce voltage drop that is withing the constraints. Similarly for feeders 1 and 3, HeatNet is not trying to minimise voltage drop.
- There is a possibility that HeatNet could achieve a slightly greater peak demand reduction if voltage constraint is not an issue e.g. shorter feeder, or vice versa.

Feeder 2 Demand and Voltage Profiles



Feeder 2 is about 1.7 km long to which 84 customers are connected, of which 78 are domestic

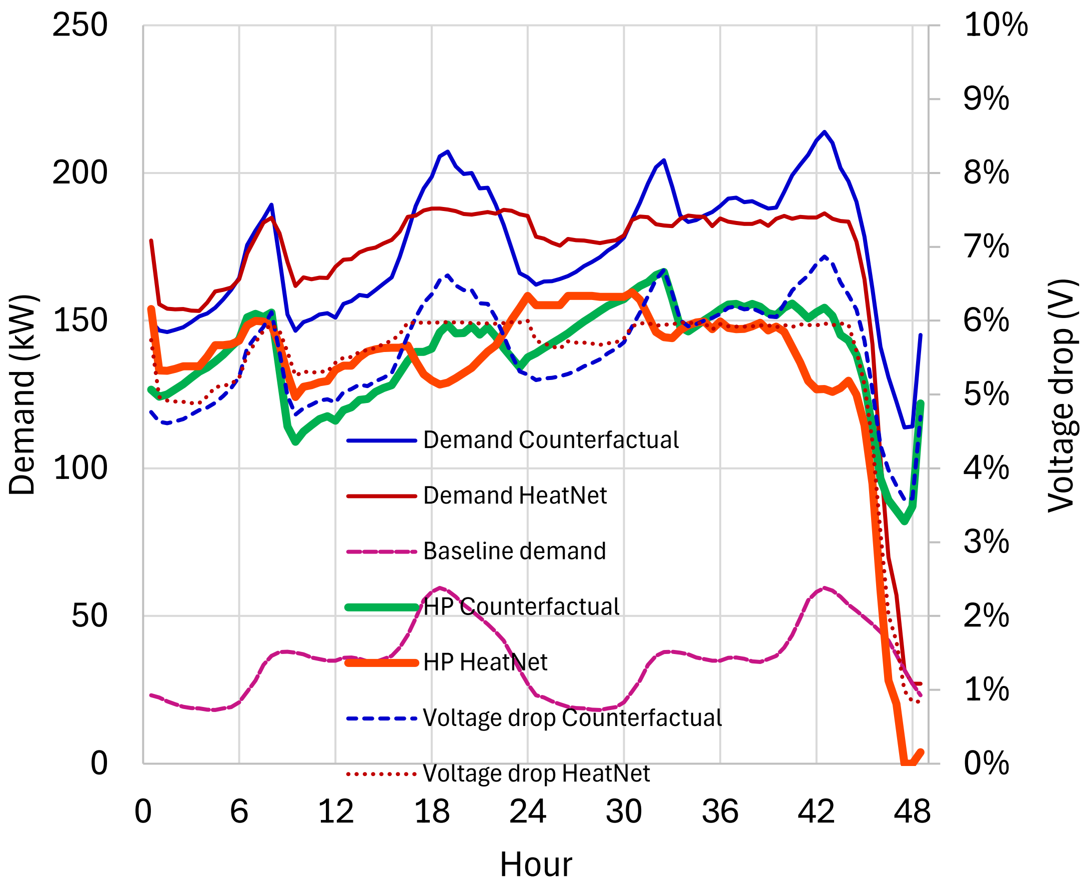
Maximum 58 domestic HPs could be installed when HetNet control is applied that is driven by voltage drop limit of 6%

- In case of Counterfactual maximum voltage drop is 7.2% i.e. HeatNet can reduce voltage drop by 1.2% (=7.2-6)

At the same time peak demand is reduced to 219 kW when HeatNet control is applied

- In case of Counterfactual peak demand is 248 kW i.e. HeatNet can reduce peak demand by 11.7%
- HP load at the time of peak is reduced from 164 to 122 kW i.e. by 25.8%

Feeder 4 Demand and Voltage Profiles



Feeder 4 is about 0.8 km long to which 64 customers are connected, of which 62 are domestic

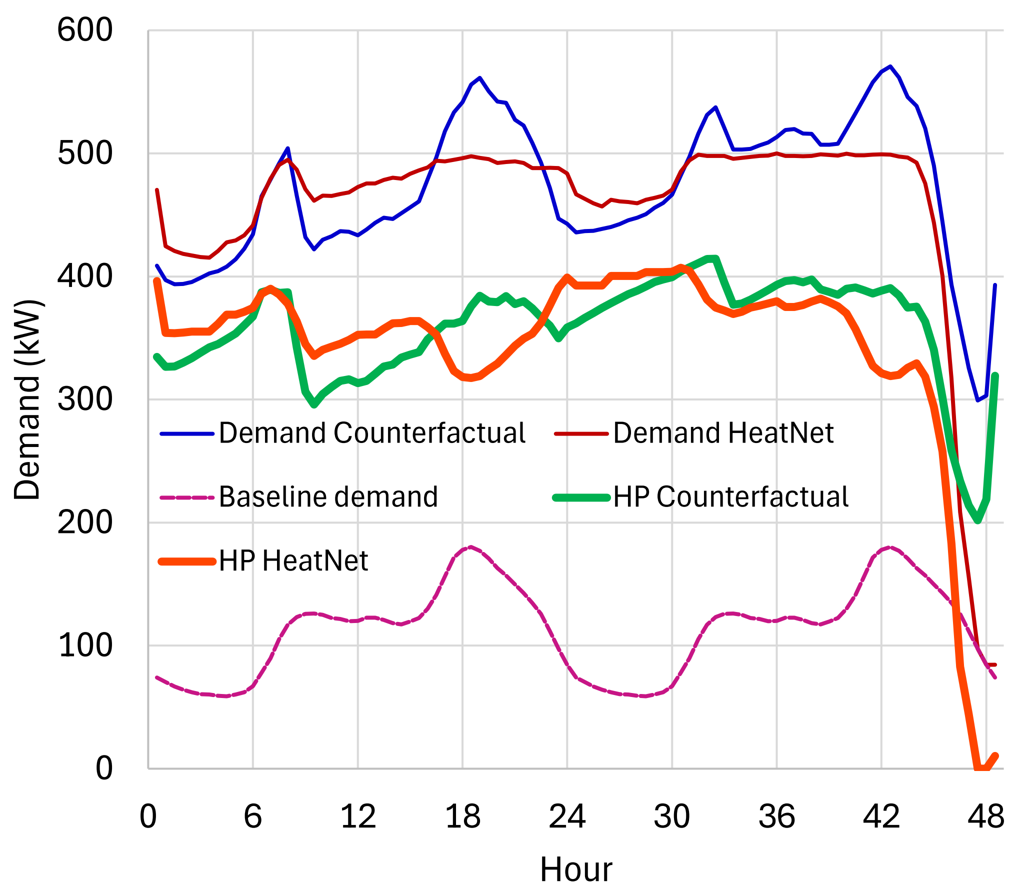
Domestic HPs could be installed in each home when HetNet control is applied that is driven by voltage drop limit of 6%

- In case of Counterfactual maximum voltage drop is 6.9% i.e. HeatNet can reduce voltage drop by 0.9% (=6.9-6)

At the same time peak demand is reduced to 188 kW when HeatNet control is applied

- In case of Counterfactual peak demand is 214 kW i.e. HeatNet can reduce peak demand by 12.1%
- HP load at the time of peak is reduced from 154 to 127 kW i.e. by 17.9%

Distribution Transformer Demand Profiles



Distribution transformer supplies 181 customers, of which 172 are domestic, through four feeders

Domestic HPs could be installed in each home when HetNet control is applied that is driven by voltage drop limit of 6% at LV feeders

Peak demand is reduced to 500 kW when HeatNet control is applied

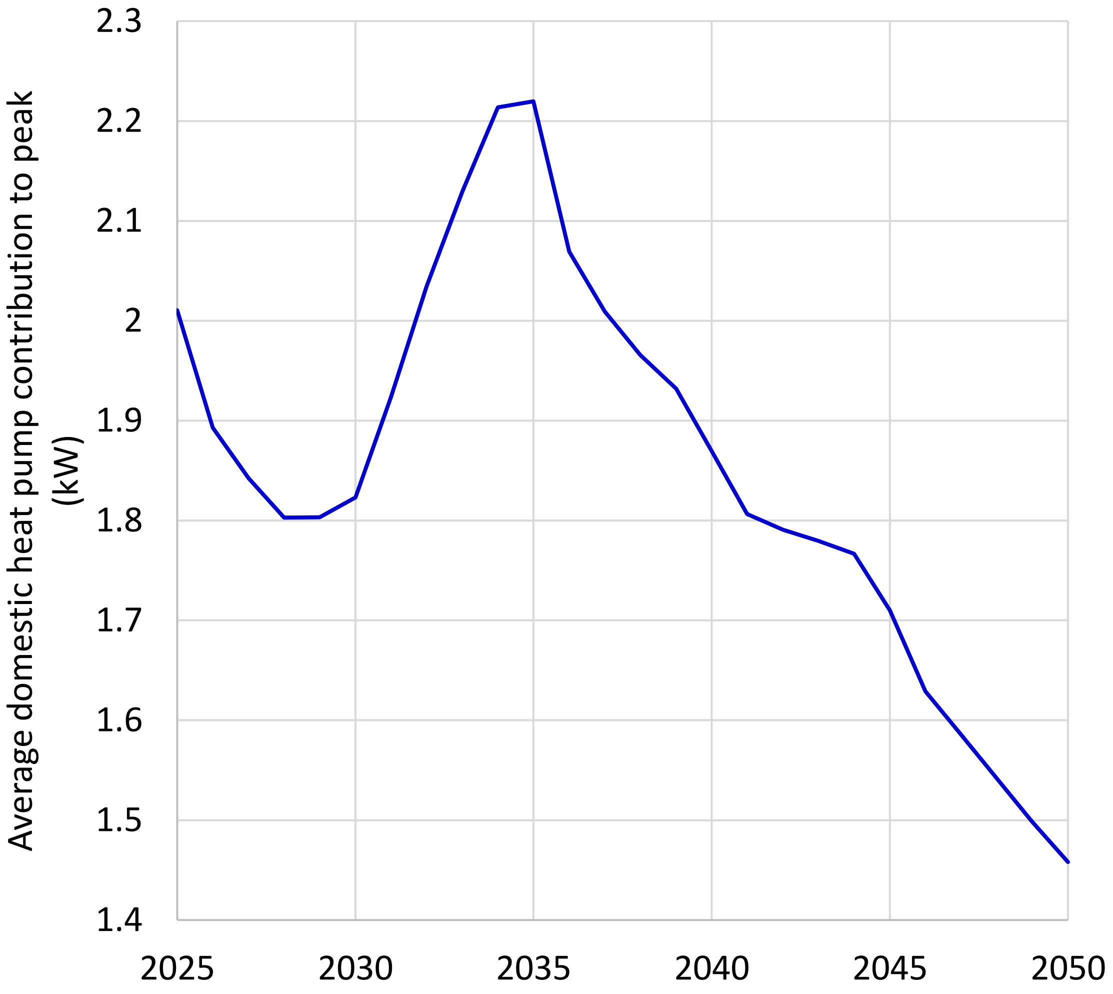
- In case of Counterfactual peak demand is 571 kW i.e. HeatNet can reduce peak demand by 12.4%
- HP load at the time of peak is reduced from 391 to 319 kW i.e. by 18.3%
  - Objective was to reduce feeder voltage drop and potentially the HP load could be further reduced by optimising HP control in feeders without voltage limit issues

Scenario Modelling
Source: National Energy System Operator (NESO), FES 2024

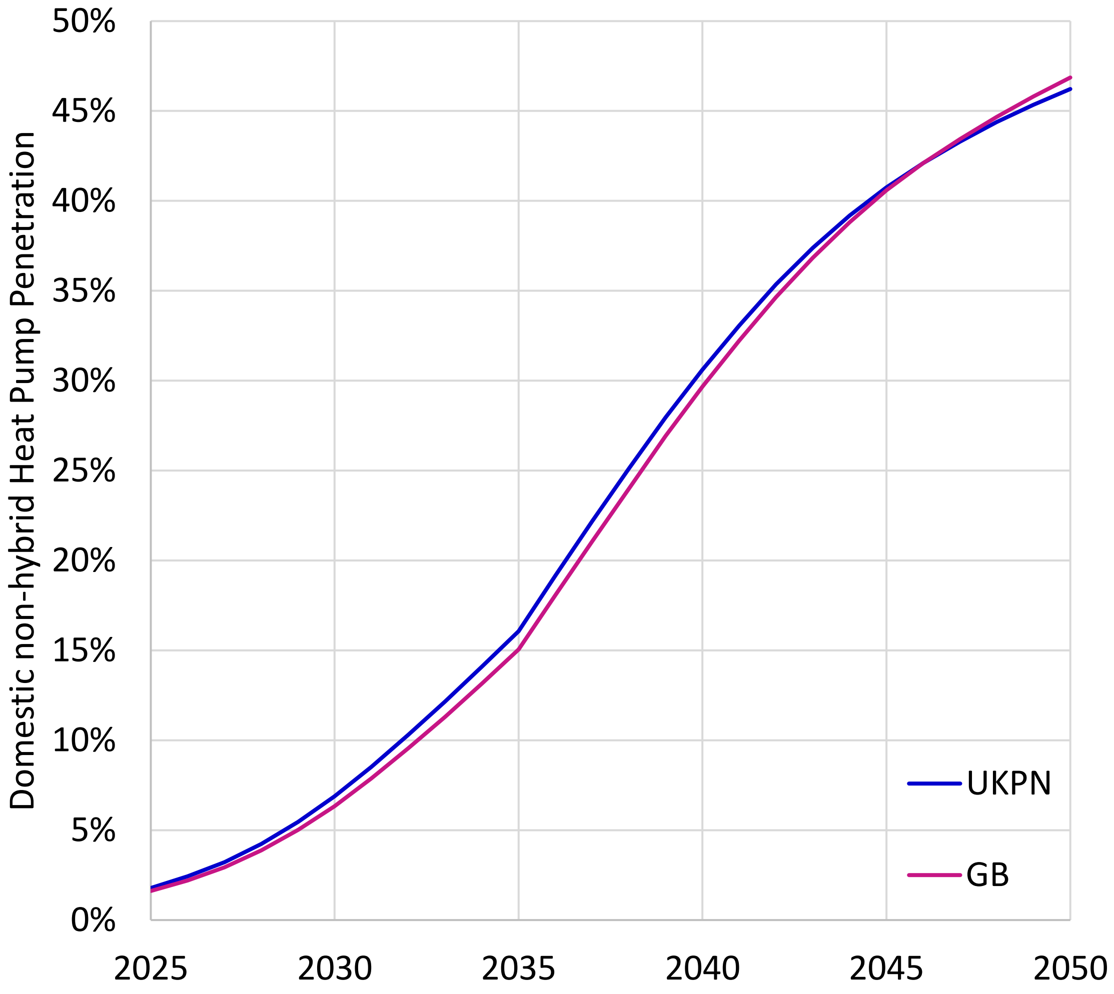
Selected Future Energy Scenario (FES) 2024 Pathway
Electric Engagement:
- Net zero met through mainly electrified demand
- Consumers are highly engaged in the energy transition through smart technologies that reduce energy demands, utilising technologies such as electric heat pumps and electric vehicles

Average heat pump contribution to peak is calculated as ratio of domestic heat pumps and number of domestic heat pumps at GB level

Assumptions
- Hybrid heat pumps do not contribute to peak
- Non-domestic heat pumps are not included in the HeatNet analysis



Domestic (non-hybrid) Heat Pumps Penetration
Source: National Energy System Operator (NESO), FES 2024

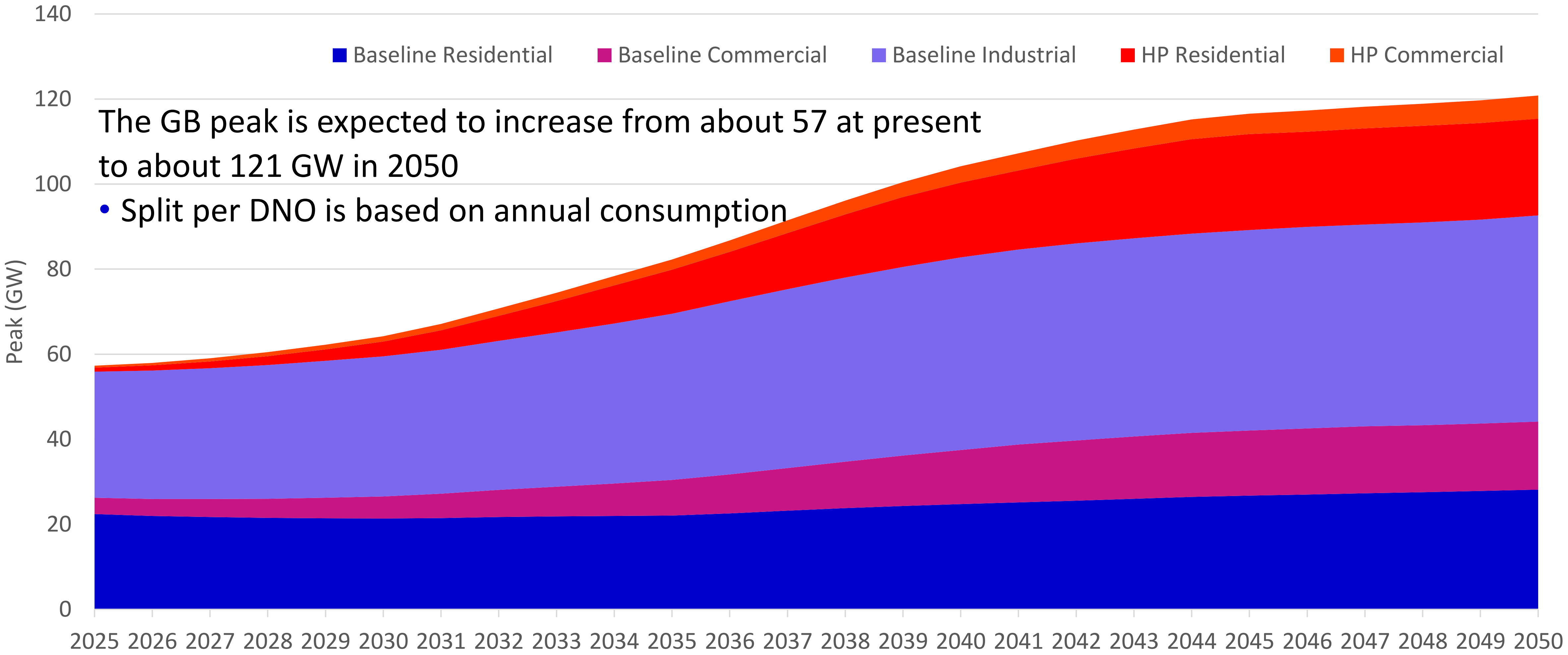


Domestic heat pump penetration is ratio between number of domestic non-hybrid heat pumps and number of domestic customers

- Very similar values for UKPN and GB regions
  - Values for UKPN region are very slightly greater until 2046, whilst values for GB regions are very slightly greater after 2047
- Penetration would increase from about 2% at present to about 46-47% in 2050

Baseline profile

Source: National Energy System Operator (NESO), FES 2024



The GB peak is expected to increase from about 57 at present to about 121 GW in 2050

- Split per DNO is based on annual consumption

Assumptions

Passiv control

- HP peak reduction is 6% for all penetrations/years
- LV voltage drop limit is 6% (statutory voltage limit)

HeatNet control

- HP load at peak reduction is 18.3% for all penetrations/years for calculation of impact on distribution transformers and upstream networks
- LV voltage drop limit is 7.2% for calculation of impact on LV networks

Random distribution of HPs to representative network customers

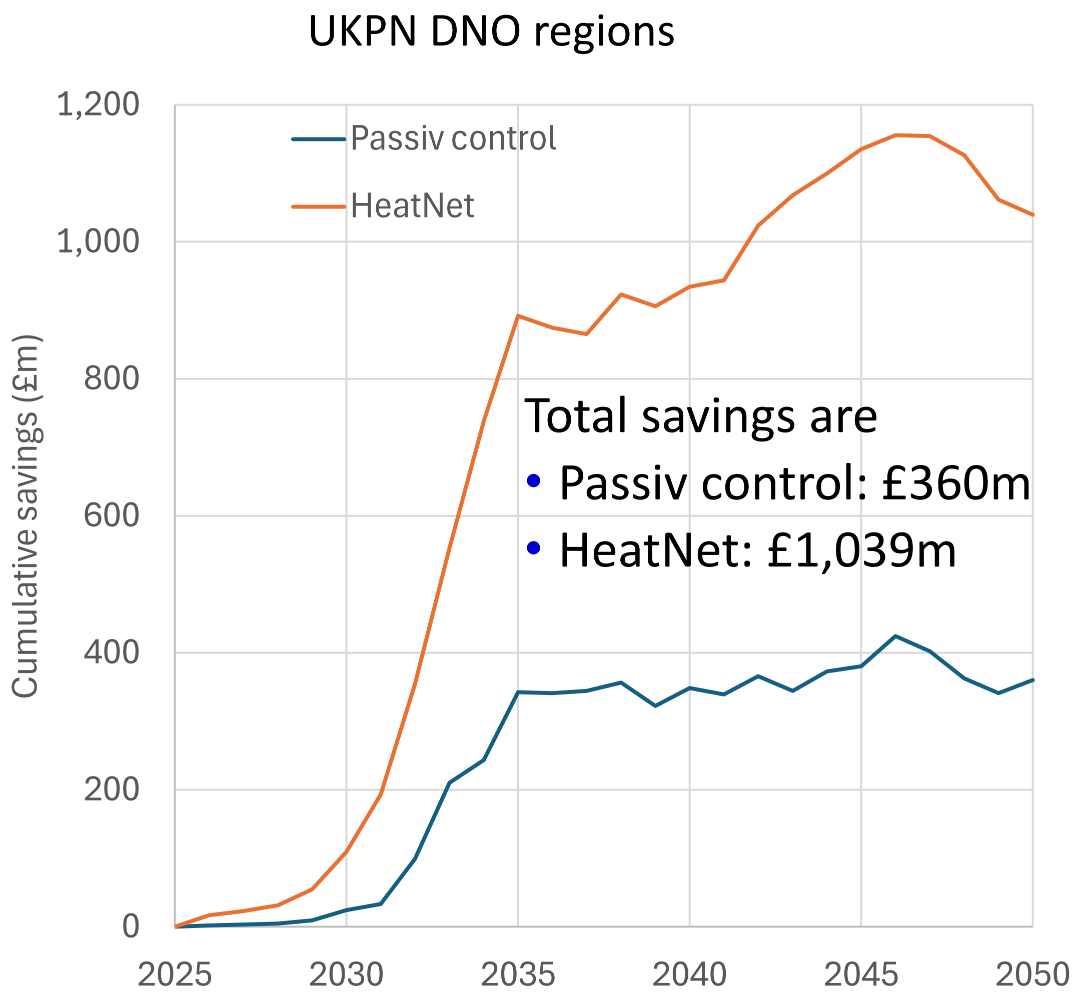
Full participation to HP control

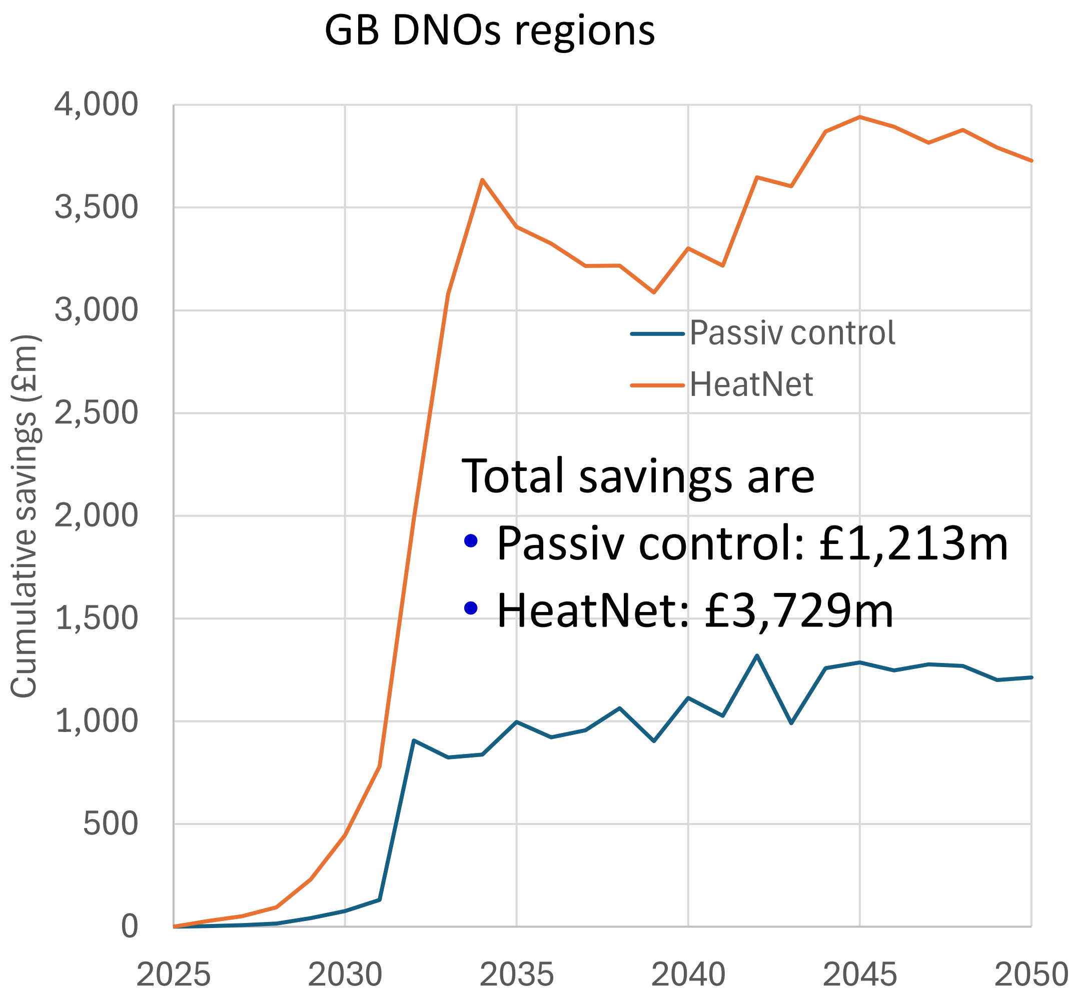
Impact of domestic non-hybrid HP is considered

- Impact of domestic hybrid HP is assumed zero (switching to gas during distribution network congestions)
- Impact of other flexibility is not considered

DNO Network Reinforcement Cost Savings

Reinforcement cost savings are calculated by subtracting control scenario reinforcement cost from counterfactual scenario

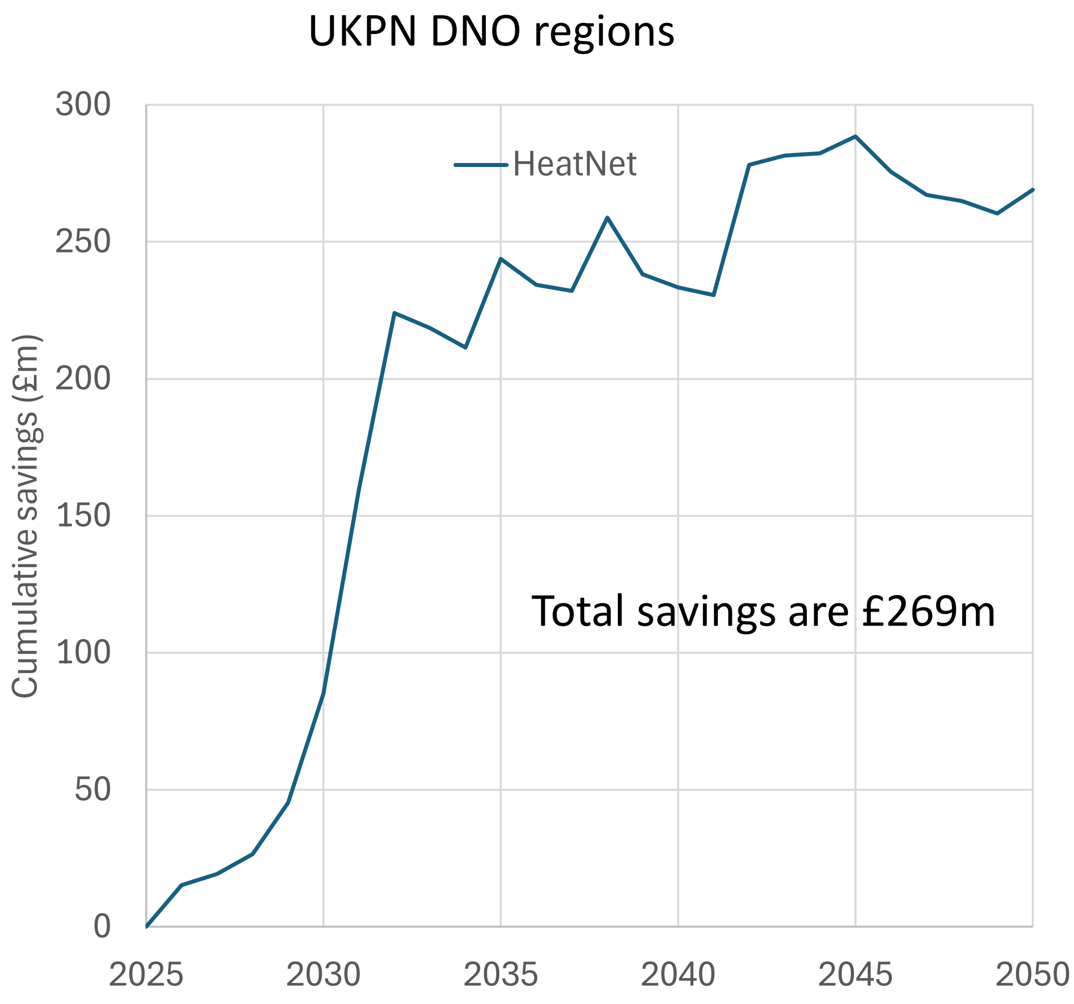


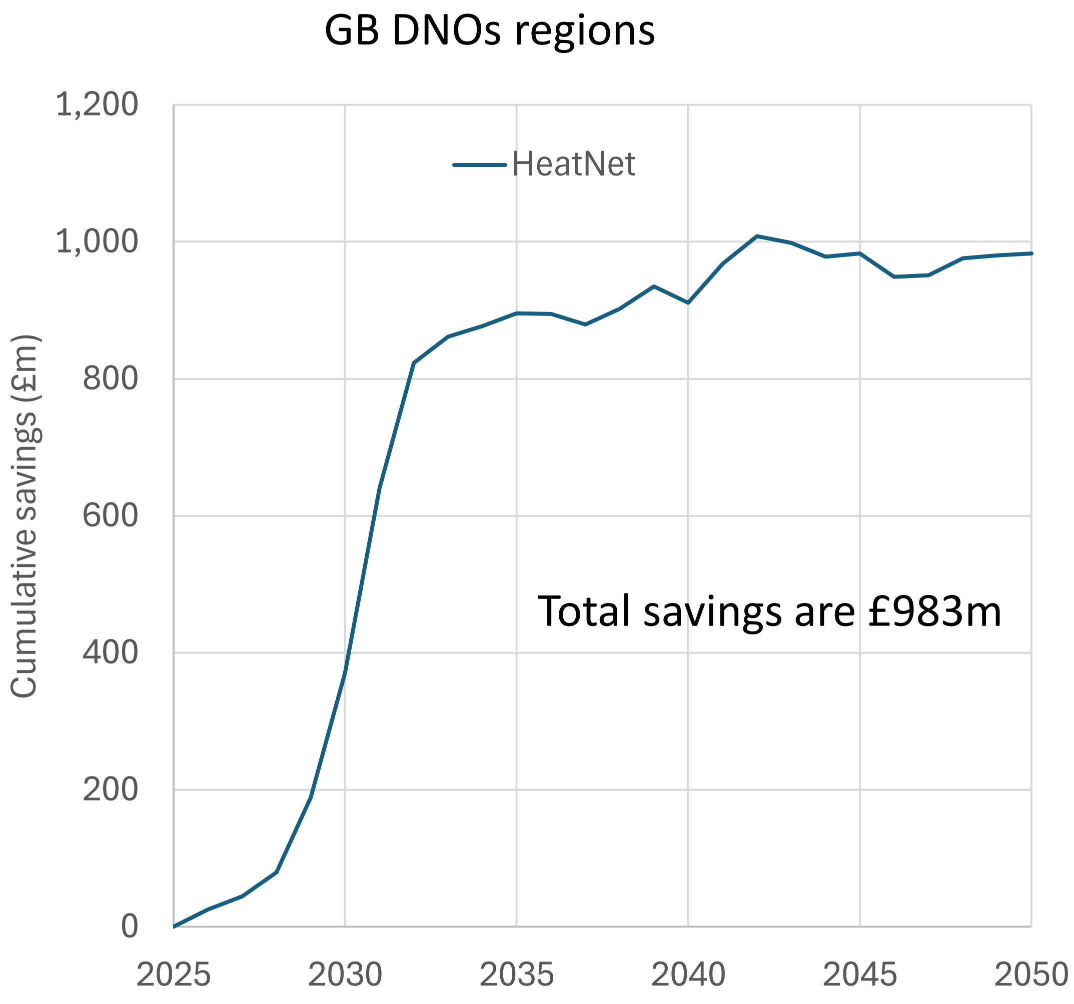


Assumptions: unit price base is 2015 and no inflation

LV Network Reinforcement Cost Savings in HeatNet

Reinforcement cost savings are calculated by subtracting control scenario (increased voltage drop limit) LV network reinforcement cost from Passiv control scenario





Assumptions: unit price base is 2015 and no inflation

Potential Benefit of Deferring Distribution Network Investment

Description of option	Net Present Values (NPVs) of deferral of distribution network investment based on payback periods/ relative to baseline (£m)				
	10 years	20 years	30 years	45 years	Whole Life
HeatNet (UKPN)	154	645	965	1,197	1,270
HeatNet (GB)	807	2,457	3,571	4,397	4,640
Passiv control (UKPN)	50	226	336	417	442
Passiv control (GB)	230	728	1,111	1,385	1,469

Assumptions

- Price base 2023/24
- Number of HP by 2050 is about 4.9m (UKPN) and 15.6m (GB) in Electric Engagement pathway

Description of option	Net Present Values (NPVs) of deferral of distribution LV network investment based on payback periods/ relative to Passiv control (£m)				
	10 years	20 years	30 years	45 years	Whole Life
HeatNet (UKPN)	80	199	274	332	348
HeatNet (GB)	308	750	1,020	1,229	1,285

For UKPN region, whole life NPV of deferral of distribution network investment is £1,270m (£260 per HP) of which

- £422m (£90 per HP) is due to reduced HP load at peak in Passiv control
- £348m (£71 per HP) is due to reduced lower voltage limit on LV networks in HeatNet
- The rest is due to further reduction of HP load at peak in HeatNet excluding impact on LV networks

For GB, whole life NPV is £4,640m (£297 per HP)

- £1,469m (£94 per HP) is due to reduced HP load at peak in Passiv control
- £1,285m (£82 per HP) is due to reduced lower voltage limit on LV networks in HeatNet
- The rest is due to further reduction of HP load at peak in HeatNet excluding impact on LV networks

Key Findings

Compared to Counterfactual, HeatNet could potentially reduce voltage drop at LV feeder by about 16% and peak by about 12% that is achieved by reducing HP load at peak for about 26%

- At distribution transformer level, HP load at peak is reduced by about 18%

Electric Engagement FES2024 is used as input potentially resulting in greater savings due to higher electrification of heat sector

- Average domestic heat pump demand would reduce from about 2 kW at present to about 1.45 kW by 2050 (maximum is about 2.2 kW in 2035)
- Penetration of domestic non-hybrid heat pumps will increase from about 2% at present to about 46-47% by 2050

Potential whole life DNO network reinforcement cost savings (NPV) are

- UKPN: about £1.3bn (£260 per domestic non-hybrid HP)
- GB: about £4.6bn (£297 per domestic non-hybrid HP)
- Significant amount of savings are achieved between 2030 and 2035

Assumptions

- Counterfactual assume manufacturer control, but it could be mix of manufacturer and Passiv controls
- Domestic hybrid heat pumps do not contribute to network congestion
- Control of non-domestic heat pumps is the same for all scenarios

Task 4.3 Review of alternative approaches

Review and development of alternative approaches for integrating HeatNet technologies into distribution network planning

Inclusion of HeatNet in network planning

Objective: How should network planner include HeatNet in network planning

Assuming worst case scenario, e.g. 100% coincidence factor of HPs, the network capacity would be planned for full HP installed capacity

- Observed counterfactual coincidence factor of HPs is 0.964

HeatNet could reduce impact of peak and/or voltage drop increase by controlling operation of domestic HPs to mitigate thermal and voltage network congestions while maintaining consumer comfort level

- Peak reduction 18% (for distribution transformer and upstream network)
- Allowed voltage drop increase for 16% i.e. from 6% to about 7.2% for LV network
- Coincidence factor reduction by 7%
- Implementation of HeatNet requires communication

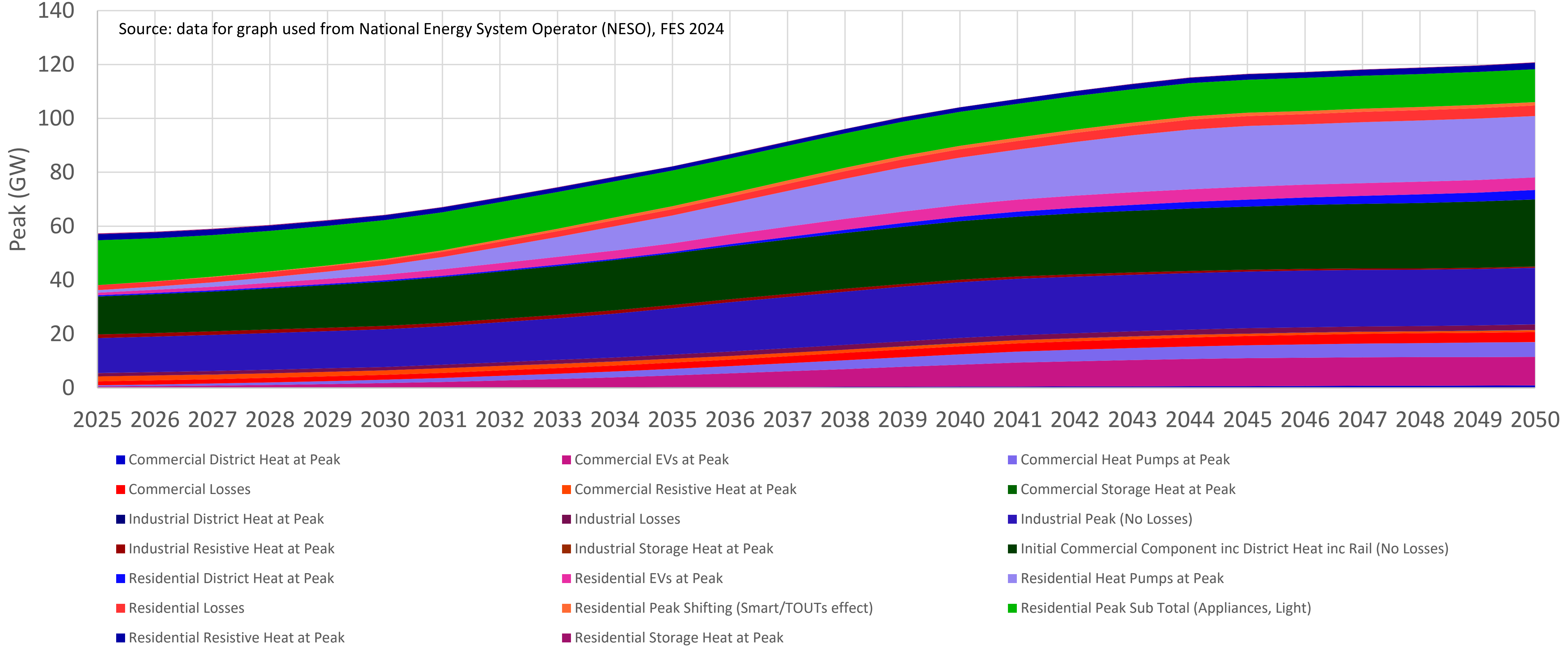
Inclusion of uncertainty in

- Short-term demand forecast
- Impact of HV network on LV network voltage
- Impact of phase and load unbalance
- Impact of manual change of set point by customer e.g. holiday or different events
- Impact of installing different sizes and characteristics of HPs
- Impact of long cold spells

Consideration of impact of

- Development of customers participation in flexibility
- Another flexible load
- Interaction between other energy technologies
- Security of supply contribution
- Other incentives such as for supply interruptions and network technical losses

Breakdown of GB peak development



Breakdown of GB peak development

Source: National Energy System Operator (NESO), FES 2024

Peak component (GW)	2025	2035	2050
Commercial District Heat	0.080	0.262	0.908
Commercial EVs	0.427	4.381	10.592
Commercial Heat Pumps	0.448	2.400	5.445
Commercial Losses	1.448	2.335	3.770
Commercial Resistive Heat	1.865	1.390	0.698
Commercial Storage Heat	0.001	0.003	0.029
Industrial District Heat	0.005	0.014	0.087
Industrial Losses	1.227	1.593	2.002
Industrial Peak (No Losses)	12.972	17.200	21.000
Industrial Resistive Heat	1.353	1.173	0.456
Industrial Storage Heat	0.000	0.000	0.008
Initial Commercial Component	14.088	19.121	24.923
Residential District Heat	0.455	0.538	3.529
Residential EVs	0.928	3.227	4.666
Residential Heat Pumps	0.958	10.343	22.750
Residential Losses	1.837	2.362	3.944
Residential Peak Shifting (Smart/TOUTs effect)	0.042	1.091	1.221
Residential Peak Sub Total (Appliances, Light)	16.658	13.226	12.268
Residential Resistive Heat	2.237	1.481	2.348
Residential Storage Heat	0.264	0.127	0.182
Total	**57.294**	**82.267**	**120.825**

Increase in peak is driven by

- Increase in residential HPs (significant) and EVs (moderate) and decrease in residential appliances and light (moderate)
- Increase in commercial EVs (significant), commercial HPs (moderate) and decrease in commercial resistive heating (low)

Given relatively high contribution to peak, impact of flexibility of EVs and commercial HPs should be also considered

- For example, when controlled daily load profile becomes flat, it might not be possible to further reduce peak

Lessons Learned and Recommendations for Beta Phase Investigations

Understanding of HP planning load characteristics

- Coincidence factor of heat pumps load at peak could be reduced by about 7% from 0.964 to 0.901
- Heat pump diversified peak at time of network peak could be reduced by about 18% (distribution transformer level) and by about 26% (LV feeder level)
- Equivalent voltage drop improvement at LV network is about 16% i.e. equivalent to relaxing minimum voltage from 0.94 to 0.93 p.u. in load flow studies

Potential gross savings (whole life NPV) for assumed Electric Engagement pathway from FES2024 are between £260-297 per domestic non-hybrid heat pump considering full participation to Passiv control and HeatNet.

Recommendations for Beta phase

- Carry out analyses using individual, rather than diversified, profiles for base demand
  - Test to establish that distribution of customer baseline annual consumption is representative
- Carry out analyses of HeatNet capability in case of random distribution of HPs to homes
- Deduce likely HeatNet start year of implementation and uptake
- Repeat GB DNO benefit analyses using HP load simulation results obtained in Alpha phase and potential trial results in Beta phase
- Consider impact of flexibility uptake and another sources of flexibility, e.g. smart control of EV charging
- Develop HP archetypes that could be used in distribution network planning
- Develop factors for inclusion of uncertainty in LV network planning