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The Impact of Energy System Decarbonisation and Decentralisation on Scotland's Electrical System – Interim Summary

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Introduction

Energy systems within Scotland have traditionally relied on large, centralised sources providing energy to homes and businesses throughout the country. However, there has recently been both desire for, and progression towards, a greater emphasis on local energy. The changing landscape of Scotland's energy systems, brought about by an increasing drive for decarbonisation and sustainability, presents an opportunity for local energy systems which better connect local energy demand with new local renewable resources.

One of the three core principles of the Scottish Governments Energy Strategy [1] is for energy systems to move towards a smarter, local model. The purpose of a CXC fellowship at the University of Strathclyde is to get a detailed understanding of the opportunities for, and implications of, Scotland moving towards smart local energy systems that are driven by sustainable decarbonising energy resources.

One of the main outputs of this fellowship is the development of a toolset, the Energy Flow Scotland (EFS) toolset. The EFS draws on other models to quantify energy flows, including both the anticipated demand and likely supply of energy. The models do this at high resolution, meaning that it calculates these energy flows at an hourly level. Importantly, the models quantify predicted energy flows at a district level, allowing for analysis of local energy demand and resources at a local level under different future energy scenarios. This toolset allows analysis of local energy demand and resources across Scotland under different future energy scenarios.

There is significant potential to reduce carbon emissions by meeting heat and transport demand with electricity generated from renewable resources. Therefore, this fellowship has a specific focus on the impact of such changes on Scotland's electrical systems. In particular, the fellowship analyses how changes to electrical demand and generation, as a result of system decarbonisation, may facilitate the growth of sustainable local economies and enable local energy balancing (where renewable energy generated from local resources are used to meet local energy demand).

This summary report describes the main outputs of Year 2 of the fellowship, including:

- Development of the EFS toolset of electrical, heat and transport demand models, and renewable generation models.
- Use of the EFS toolset to model how electrical energy flows may change at electrical grid supply points (GSPs) throughout Scotland under a particular 2030 electrified energy future scenario.
- Analysis of how decarbonisation and decentralisation may impact electrical flows at particular GSPs, as well as discussion on the distinct challenges and opportunities at both urban and rural areas.

- Description on how local energy balancing may be used to reduce the need for future network reinforcements.

1. Energy Flow Scotland Toolset

The EFS toolset consists of various models that quantify high resolution energy flows at a district level. The toolset contains both demand and generation models, which represent the following:

- Residential heat demand.
- Multi-sector industrial heat demand.
- Electrical demand from heat pumps.
- Electrical demand from storage heaters.
- Plug-in hybrid electrical vehicle (PHEV) charging demand.
- Wind Power generation.
- PV Power generation.

Development and demonstration of this toolset is one of the main outputs of the fellowship.

The EFS toolset can be used to analyse future energy scenarios at a local level. This analysis can guide policy makers and industry on:

- How often a local system/area relies on national infrastructure and resources to meet energy needs.
- The areas that will require investment in the network infrastructure to meet future demand.
- How novel solutions (e.g. energy storage, real-time network management [2]) may be implemented as an alternative to traditional reinforcement.

At this stage, analysis is conducted at an electrical grid supply points (GSPs) level. There are a total of 145 separate GSPs in Scotland – refer to Section 3 for a summary of the role of electrical GSPs in Scotland's energy system.

The EFS toolset models energy demand from the homes and businesses connected to each GSP as well as output from the generators connected to them. Quantified demand and generation output from the toolset are location specific and are provided at hourly time resolution. Quantification is dependent on scenario inputs, such as the adoption rate of decarbonising technologies at each GSP.

The bottom-up models that constitute the toolset use various methodologies and data to determine demand and generation at each GSP in Scotland. This basic methodology is outlined in Figure 1. The impact of new demand and generation on electrical flows at each GSP is determined by comparing modelled future scenario flows with a 2015-16 base case [3].

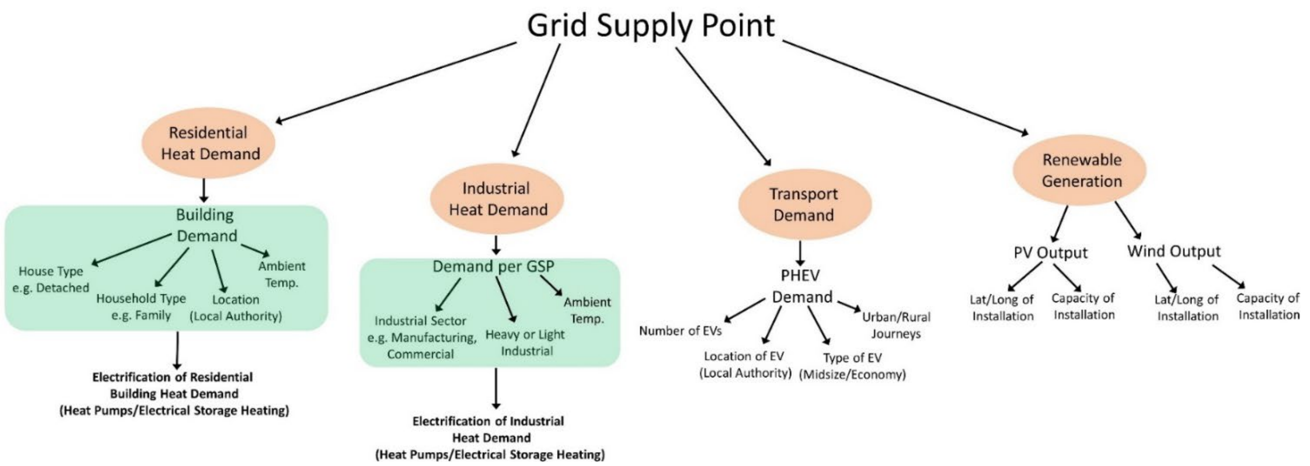
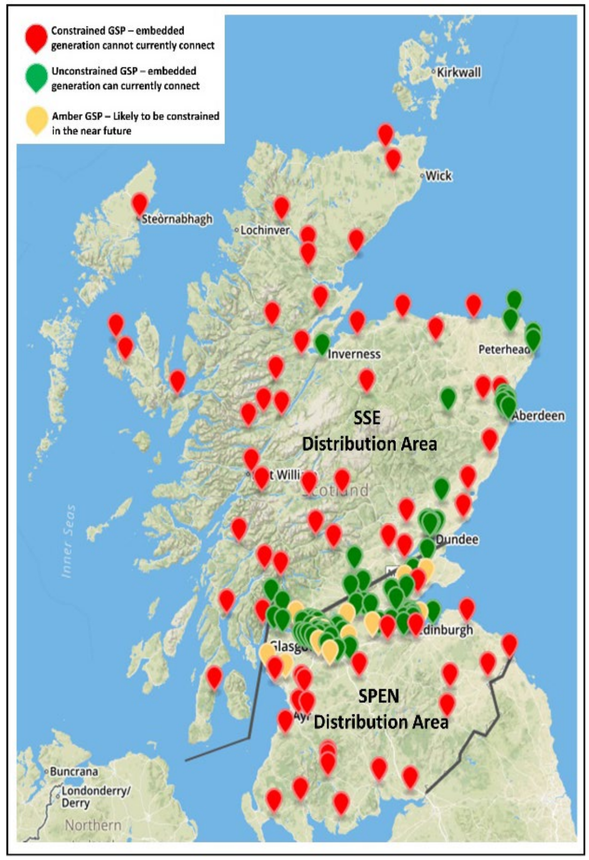


Figure 1: Modelling of energy demand and resources within the EFS toolset at an electrical grid supply point

2. Electrical Grid Supply Points

GSPs are the electrical connections between the transmission and distribution networks. The EFS toolset models how flows at these points in the electrical system will change as a result of low carbon technology uptake and adoption of local energy economies. There are a total of 145 GSPs in Scotland[1] – 83 are owned and operated by Scottish Power Energy Networks and the remaining 62 by Scottish and Southern Energy Networks. Figure 2 illustrates their locations across Scotland[2] and provides an indication of their ability to accommodate new generation [4], [5].



Data was available describing the electrical flow throughout a base case period of 2015-16 at each of these GSPs [3]. The number of residences, vehicles associated with these residences, businesses and industries connected to each GSP was extrapolated from the most recent Census data [6]. Modelled demand from low carbon, electrified heat and transport technologies adopted by homes and industries connected to each GSP under future energy scenarios can be compared using the EFS toolset with 2015-16 base case data to determine the impact on local electrical energy flows. Renewable generation models within the toolset can also be used to understand the impact that new, local energy resources will have on local electrical energy flows.

[1] Due to data limitations, analysis at this stage has only considered GSP flows at 128 of the 145 GSPs

[2] Map available at: http://geojson.io/#id=gist:rory87/0707caaff7b5292d65f4a55dc76e69b4&map=6/56.765/-4.230

3. Future Energy System Scenarios

Figure 2: Map of GSPs in Scotland. GSPs marked red are constrained to new generation connections[2]

For undertaking analysis at a GSP level, future energy scenarios were modelled through the distribution of technologies to each GSP.

In particular, the technology driven scenarios describe:

- Domestic Heat Electrification - the percentage of households connected to each GSP that adopt heat pumps or electrical storage heaters to supply their heat demand.
- Transport Electrification - the percentage of conventional vehicles (associated with households connected to each GSP) that switch to EVs.
- Energy Resource Decarbonisation - the installed capacity (and number) of new renewable generation connected to the local networks.
- Non-Domestic Heat – the rise/fall in industrial and commercial (I&C) heat demand and the percentage of industries connected to each GSP that adopt electrified heat technologies.
- Electric Demand – the rise/fall in end-use domestic and I&C electrical demand at each GSP, not including heat and transport end-uses.

The uptake of technology at each specific GSP was considered to be dependent on its characteristics and location. In particular, for many components of the scenario, it is important to consider the nature of the area serviced by each GSP. Here for simplicity, each GSP is classified as Urban, Sub-Urban or Rural. The Scottish Government 8-fold Urban Rural classification [7] was used to describe each GSP in Scotland according to these area types.

This process of classifying GSPs across Scotland into a specific category simplifies the implementation of technology driven scenarios i.e. instead of considering each GSP individually, groups of GSPs can be attributed a certain percentage of technology uptake depending on their 8-point classification.

4. 2030 Electrical Scenario Development

A 2030 energy system scenario has been developed and analysed using the EFS toolset. This scenario partly follows the Scottish Government scenario of an electrified energy future, as outlined in the Energy Strategy [1], and examines one of their electrification pathways in Scotland. A base case scenario was also prepared using 2016 data that represents the system of 'today', and this was used within the tool set as a start point for analysis.

At this stage, the main purpose of scenario development is to outline the type of analysis that this toolset enables and neither of the reported scenarios are considered prescriptive.

Table 1 summarises low carbon technology uptake and new generation resources across 128 of the 145 Scottish GSPs3 for the 2030 scenario. Figures 3 and 4 illustrate the relative difference across components between the base case and the 2030 future scenario.

The main differences include:

- EVs accounting for 44% of all vehicles on the road (excluding industrial/haulage vehicles).

[3] Limitations in data meant that only 128 of the 145 GSPs were included in this scenario and resulting analysis.

- 27% more homes using electrified heating as their main source of heat – this includes a mix of both heat pumps and electrical storage heaters.
- Total installed embedded renewable generation capacity increasing from 5.6GW to 12.4GW.

For each of these two scenarios simulation studies using the EFS toolset were conducted and in the following section model results and comparative analysis are provided4.

[4] Uptake at each separate GSP is dependent on its specific characteristics and rate of technology adoption at each GSP may differ. Note that neither of the scenarios presented include models of novel system storage and control of energy flows.

Table 1: Breakdown of 2030 future scenario components across all Scottish GSPs

Domestic Heat	Homes with Non-Electric Heating	Homes with Heat Pumps	Homes with Storage Heaters
	1,301,709	288,030	594,508
Transport	Non-Electric Vehicles	Plug-in Hybrid EV	Full EV
	1,568,021	913,470	391,487
Wind Generation	Total Installed Capacity (GW)		
	10.6		
Photovoltaic Generation	Total Installed Capacity (GW)		
	1.8		

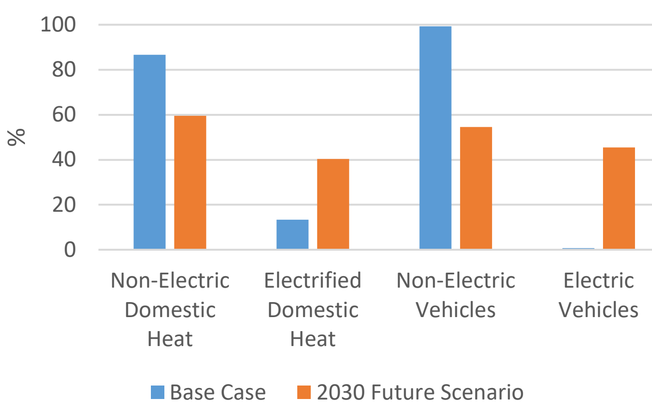


Figure 3: Differences in electrified heat and transport between base case and future scenario

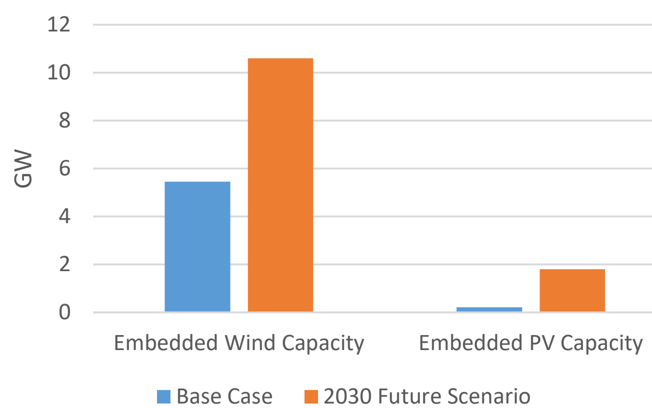


Figure 4: Differences in embedded generation between base case and future scenario

5. Analysis of the 2030 Electrical Scenario – Key Results & Findings

The EFS toolset was used to model electrical demand, generation and flows at each Scottish GSP in the 2030 future scenario, and these were compared to the 2015/16 base case.

The main findings are:

- The electrification of heat and transport demand results in an additional 11.4TWh of annual electrical– this equates to a 28.6% increase of base case electrical demand[5].
- Electrification of heat contributes 8.6TWh of the increase in annual demand while transport electrification adds 2.8TWh, as illustrated in Figure 5.
- Annual energy imports across all GSPs into local areas will increase from 20.7TWh to 26.7TWh – in this sense, energy is imported to meet local demand from resources out with the local area connected to a GSP i.e. from large transmission connected generation or generation embedded within other local areas.

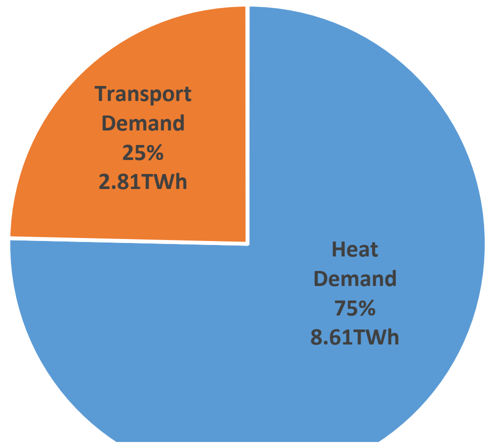


Figure 5: Breakdown of low carbon technology demand

- Annual energy exports across all GSPs from local areas will increase from 3.5TWh to 18.7TWh. This represents a significant increase in total local exports. Energy exported from GSPs will be used to meet both demand across other local areas throughout Scotland and may also be exported to other regions of the GB network (e.g. England and Wales) and/or other national electrical systems where interconnection exists (e.g. the Island of Ireland system) or may exist in the future.
- Despite the electrification of heat and transport increasing demand at GSPs by 11.6TWh, energy imports only increase by 5TWh. This indicates that within the modelled 2030 future scenario, 6.6TWh of this demand will be met by new local generation. In the event that no additional generation is connected locally, demand from low carbon technologies would have to be met from resources out with the local area.
- Total annual electrical demand across all GSPs rises from 39.8TWh in 2015/16 to 54TWh by 2030 – this is representative of demand from users directly connected to the distribution (medium voltage and low voltage) networks and does not include demand from large consumers that are directly connected to transmission system.

Analysis of individual GSPs under this specific scenario yielded the following key themes:

[5] The modelled scenario assumes that the increased uptake of electrified goods and technologies by 2030 (i.e. end-use electrical demand) will result in a general 5% increase on the base case electrical demand (≈ 2TWh).

- The extent of demand growth in urban areas as a result of EVs and electrified heating will result in approximately 75% of urban GSPs requiring capacity reinforcement by 2030.
- The connection of new renewable generation in rural areas would result in 58% of rural GSPs requiring reinforcement to meet peak export requirements in 2030.
- Figure 7 illustrates the modelled 2030 peak demand for all 128 Scottish GSPs as a percentage of current GSP rating. Peak ratings could either be positive, implying an import peak, or negative, implying an export peak. These results highlight that, under existing ways of operating the networks, 103 (80.5%) of GSPs would need some form of reinforcement. 44 GSPs (34%) would need reinforced to double the existing capacity, while 22 (17%) would need to be reinforced to four times the existing capacity – this level of reinforcement works would typically be at rural GSPs that currently have limited capacity and where large amounts of new renewable resources may be connected.

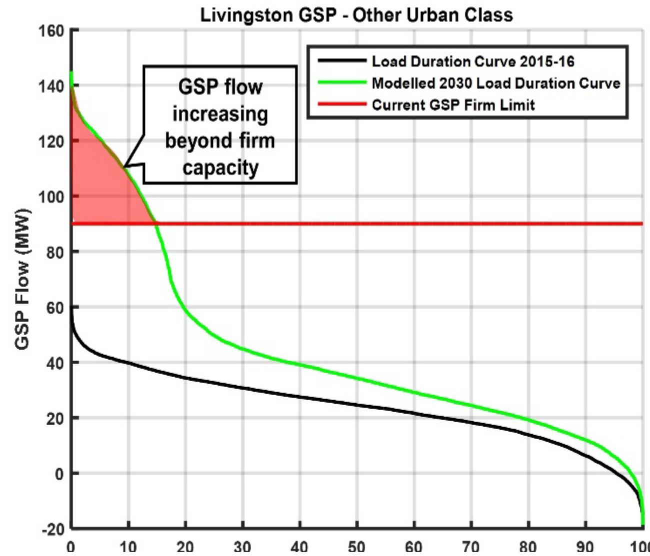


Figure 6: Example load duration curve for an urban GSP. A positive GSP flow indicates that energy is being imported from into a local area to meet local demand; a negative GSP flow indicates that energy from local generation is being exported from a local area to the transmission (national) system.

- GSP load duration curves[6] highlighted that electrical imports at an 'average' urban GSP would breach firm limits[7] between 5 to 10% (440 to 880 hours) of the year in 2030 – in the absence of technologies and techniques, such as energy storage and demand response, that provide greater flexibility and control within electrical systems, some of these assets would need to be reinforced to over double the existing capacity. A load duration curve describes the percentage of time where a certain minimum level of electrical demand (load) at an asset is present. A GSP 'firm limit' relates to the maximum electrical demand that an asset can provide to connected customers, even in the event of a single fault occurring within the asset. Figure 6 highlights an example urban GSP load duration curve where the GSP firm limit has been breached 12% of the time in the 2030 electrical scenario (represented by the area shaded in red).

[6] The load duration curve highlights the variation of GSP demand in a downward curve, such that the load (demand) is plotted on the vertical axis and the percentage of time is plotted on the horizontal axis. The percentage of time at which a certain value of minimum loading is present can be inferred from the curves.

[7] The 'Firm Limit' of a GSP is defined as the maximum electrical demand that the substation can provide to customers connected to it in the event of a single electrical fault within the GSP i.e. even if a single fault occurs within the GSP, the firm load limit must still be met. As means of a basic example, say a GSP has two separate electrical transformers rated at 50 MW each (i.e. each can safely transfer 50MW of power at any instance). This GSP may, under normal conditions, provide a maximum demand of 100MW (2x50MW). However, the firm limit of the asset would only be 50MW, as, in the event one of two transformers failed, only 50MW could be safely provided to customers connected to the GSP.

- Existing firm limit constraints on GSPs (see Figure 2) will limit the integration of new renewable generation without either significant network investment or alternative control of the energy flows. Within these GSP areas there could be opportunities to match the implementation of decarbonised energy resources and demand.

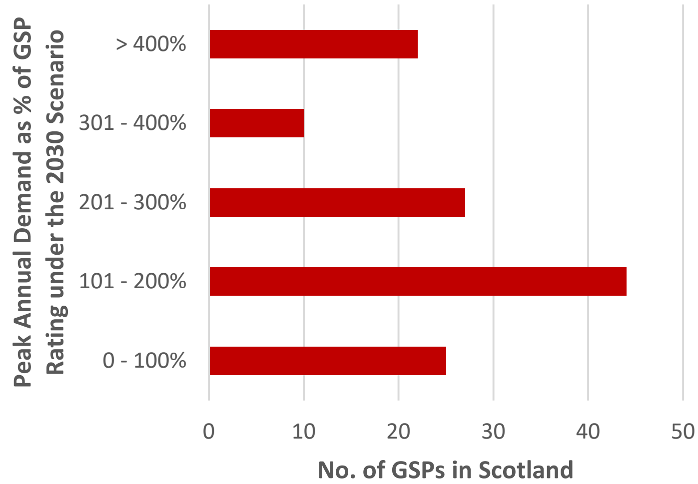


Figure 7: Modelled 2030 Peak Annual GSP demand as a % of current GSP rating. A peak demand greater than 100% implies that the GSP would require upgrading under the modelled scenario.

Consideration should be given to the main reasons for electrical GSPs (or electrical assets in general) requiring capacity reinforcement. Such reasons typically differ between urban and rural areas:

- Within urban areas, local demand is generally high whilst local generation is generally low. Hence, these areas will frequently import energy from national resources to meet their energy needs, and the local GSP will have to be rated to meet the energy import requirements.
- Conversely, within rural areas, local demand is generally low comparative to demand, while local generation capacity is generally high - in the event that local generation output exceeds local demand at a specific point in time, these areas will export energy back to the transmission (national) system. Within this particular situation, the local GSP will have to have sufficient capacity available to export energy from the local energy resources. Current network operation dictates that, in the event that the GSP does not have suitable capacity to export energy, output from local energy resources will be curtailed or not allowed to connect to the network at all.

Policy going forward should differentiate between these key urban-rural differences, and potential solutions should consider the nature of the energy characteristics of a particular area. Distribution Network Operators (DNOs) have begun identifying the need to move towards strategies focussed on a greater control of energy flows [8]. Conventionally, DNOs have operated under a passive 'fit and forget' approach, where substantial investment is made in network assets to ensure that they have the capacity to securely meet peak annual flows. However, the validity of this business model has decreased as the electrical system evolves to one where decarbonisation and decentralisation will increase the need for ever greater investment in network assets.

The transition of DNOs to Distribution System Operators (DSOs), where distribution networks are actively operated and managed, is foreseen as being a way of maintaining efficient, economic and co-ordinated networks.

Within this model, reinforcement actions of the type identified above could be substituted for smarter operation/management of local systems deeper into the network at lower system voltages. Future work in Year 3 of this fellowship will investigate how smart control of energy flows could alleviate the requirement for network reinforcements.

6. Opportunities at Constrained Areas of the Network

Constraints on the integration of new embedded renewable sources may pose significant barriers on the delivery of future energy strategies, especially if DNOs continue to operate under 'fit and forget' approaches. However, an increasing level of demand at constrained areas of the network may facilitate additional renewable connections. In this event, output from the new local connections would be used to meet the additional local demand, thus enacting a form of local energy balancing. The extent to which this is realised could help manage or even eliminate the need for GSP reinforcement as well as help meet the target for renewable sources to meet 50% of the energy for Scotland's heat, transport and electricity consumption in 2030 [1].

To appreciate how new load may be serviced by local generation, it is desirable to understand how demand increases at local areas throughout the day. The EFS toolset provides this capability.

Figure 8 illustrates the spread of average hourly increases in demand between the base case and the modelled 2030 scenario at all the constrained GSPs throughout winter months. The increases in hourly demand at the constrained GSPs are a result of the future uptake of EVs and electrified heating, as modelled in the 2030 scenario. Hourly demand increases are expressed as percentages of GSP firm limit so, for example, the 45% median increase in demand at 01:00 at a GSP with a firm limit of 100MW would equate to a 45MWh increase.

Key findings of this analysis concluded that:

- Increases in demand between 00:00 and 01:00 have a median value of 45% of GSP rating in Winter and 41% of GSP rating in Summer[8].
- Median hourly demand increases are greater than 5% throughout the day in winter, spring and autumn, rising to between 10-20% of GSP rating in the evenings.

Coincidence of new generation, demand and storage (as well as novel network management solutions) in constrained GSP areas would be a step towards local energy balancing. Detailed quantification of how demand changes at a local level will assist in guiding policies that seek to implement such innovative solutions.

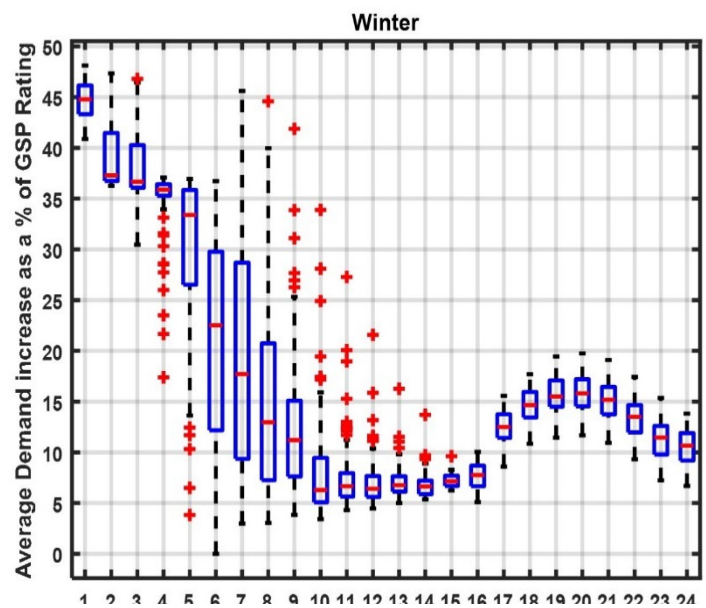


Figure 8: Average hourly demand increase across all constrained GSPs

7. Further Work

Building on these Year 2 outputs, the main aims of Year 3 of the Fellowship include:

- Modelling the integration of storage and the control of energy flows through novel techniques, such as active network management [9].
- Identification of the types of investment required at particular local levels to maintain system reliability and progress sustainable, decarbonised energy systems.

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[8] Demand from storage heaters results in large increases in demand in the early hours of the day. Note that the times in which storage heaters charge can be modified on a day-to-day basis.

- Development of in depth case studies of particular local areas of interest, including analysis of the low and medium voltage networks 'below' a specific GSP.
- Co-development of future energy system scenarios with the Scottish Government team and wider stakeholders (e.g. DNOs).

8. References

1. Scottish Government. *Scottish Energy Strategy: The Future of Energy in Scotland*. 2017 [cited 2018 September]; Available from: https://www.gov.scot/Publications/2017/12/5661/downloads.
2. Scottish Power Energy Networks. *Accelerating Renewable Connections - Closedown Report*. 2017; Available from: https://www.spenergynetworks.co.uk/userfiles/file/ARC_Closedown_Report.pdf.
3. Elexon Balancing Reports. Available from: https://www.bmreports.com/bmrs/?q=help/about-us.
4. SPEN. *Distributed Generation Heat Maps*. [cited Septmber 2018]; Available from: https://www.spenergynetworks.co.uk/pages/connection_opportunities.aspx.
5. SSE. *Generation Availability Map*. [cited 2018 September]; Available from: https://www.ssepd.co.uk/generationavailability/.
6. *Census Data Explorer*. 2011 August 2017]; Available from: http://www.scotlandscensus.gov.uk/ods-web/home.html.
7. Scottish Government, *Urban Rural Classification 2016*, Energy, Editor. 2018.
8. Scottish Power Energy Networks, *SPEN DSO Vision*. 2016. p. 38.
9. Scottish Power Energy Networks, *Flexible Connections and Principles of Access Policy*. 2017.