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TRABAJO FIN DE MÁSTER

ANALYSIS OF EXISTING LOCAL MARKETS FOR SYSTEM SERVICES, PRODUCT PRICING AND AGENT´S PARTICIPATION

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Madrid
Agosto de 2024

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

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ANÁLISIS DE LOS MERCADOS LOCALES EXISTENTES PARA LOS SERVICIOS DEL SISTEMA, LOS PRECIOS DE LOS PRODUCTOS Y LA PARTICIPACIÓN DE LOS AGENTES

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RESUMEN DEL PROYECTO

1. Introducción

El sistema eléctrico se encuentra en un periodo de gran transformación, con la creciente penetración de los recursos energéticos distribuidos (DER, por sus siglas en inglés) y la transición hacia un sistema eléctrico más descentralizado. La transformación es clave para lograr mayores logros en sostenibilidad, resiliencia y eficiencia operativa en el sistema eléctrico, así como para aumentar la penetración de las energías renovables en la matriz energética. Históricamente, las redes energéticas han sido centralizadas, con grandes plantas de generación de energía suministrando electricidad a lo largo de la infraestructura de transmisión y distribución. Sin embargo, con el avance de la tecnología de energía renovable y la tecnología de recursos distribuidos, como la energía solar y eólica mediante paneles y turbinas, respectivamente, esta configuración centralizada está evolucionando hacia un sistema más distribuido. La Figura 1 muestra esta transformación de la estructura del sistema eléctrico [1].

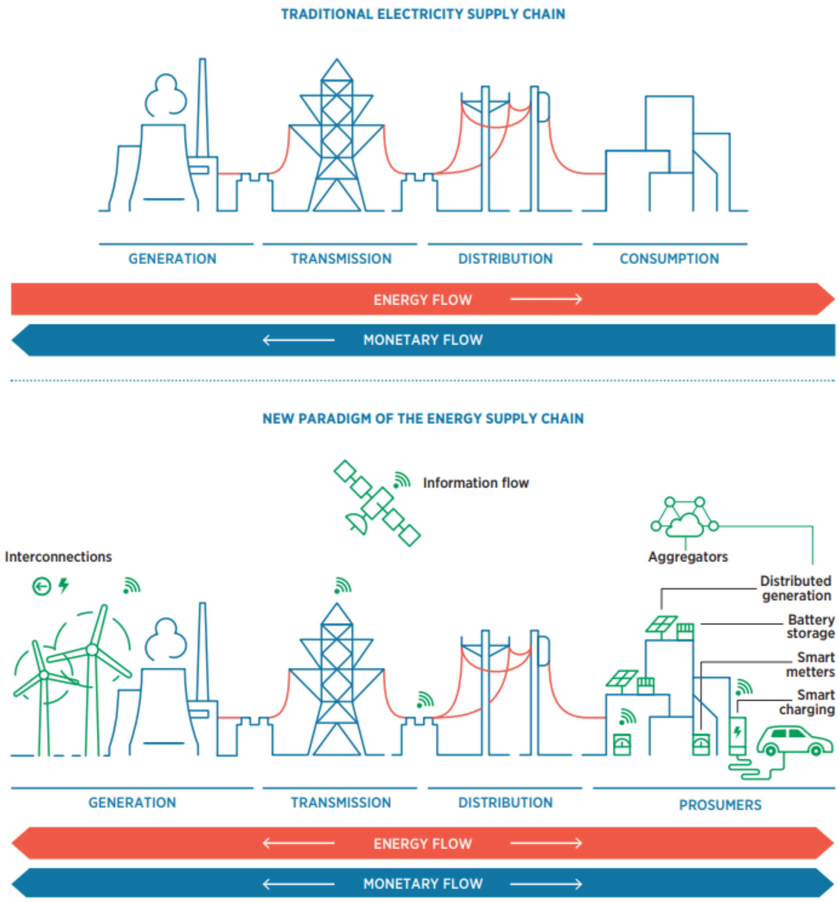

Figura 1: Transformación de la estructura del sistema eléctrico [1]

La descentralización del sistema eléctrico promueve la participación de un mayor número de diversos actores, tanto en la generación como en el consumo de energía, generando un sistema más dinámico y adaptable a la variabilidad en la demanda y suministro de energía. Esta capacidad de adaptación, entendida como flexibilidad, ha pasado a ser un tema fundamental para el mantenimiento de la estabilidad en el sistema, principalmente con la incorporación de fuentes renovables con generación variable e intermitente [2].

En este sentido, los mercados locales de servicios del sistema representan una herramienta fundamental para lidiar con la creciente complejidad del sistema eléctrico. Mediante estos mercados, los DER están habilitados para proporcionar importantes servicios para el sistema, como la regulación de la frecuencia, el control del voltaje y las reservas operativas, a través de un intercambio de energía que se ajusta a las necesidades del sistema. Las plataformas de mercados locales permiten una interacción entre proveedores de servicios de flexibilidad y operadores del sistema, a través de la cual la negociación de los servicios se puede realizar de manera eficiente y transparente.

El objetivo de esta tesis es analizar los mercados locales de los servicios del sistema, con especial interés en los mercados de flexibilidad en el Reino Unido a través de la plataforma Piclo. Para ello, se han estudiado distintos productos de flexibilidad: Secure, Sustain, Dynamic y Restore, productos que son remunerados tanto por disponibilidad (en los casos de Secure y Dynamic) como por utilización (en todos los casos), identificando las diferencias en la formación de precios y entre áreas de mercado. Así, pues, se han considerado varias variables, como la ubicación, tecnología, proveedor y tensión, entre otras, para entender mejor la formación de precios y el comportamiento de los participantes en estos mercados. En la Tabla 1 se presenta un resumen más detallado de las características de los productos estudiados.

Tabla 1: Características de los distintos productos de flexibilidad [3]

	Caso de uso	**Disponibilidad £/MW/h**	**Utilización £/MWh**	**Objetivo**
Secure	Pre-fallo	Sí, Pago	Sí, Pago	Resolver las limitaciones operativas (reducción de picos)
Sustain	Programado	No	Sí, Pago	Hacer frente a la sobrecarga prevista
Dynamic	Post-fallo	Depende del DSO	Sí, Pago	Hacer frente a una anomalía en la red o a una interrupción programada
Restore	Restablecimiento de la red tras un fallo	No	Sí, Pago	Restablecer la red

Este proyecto de investigación busca llenar un vacío en el entendimiento de los mercados emergentes de servicios del sistema, a través de la realización de un exhaustivo análisis de los distintos factores que afectan e influyen tanto en la formación de precios como en el comportamiento de los participantes. La información recopilada a través de esta investigación contribuirá al desarrollo de un sistema eléctrico más sostenible, resiliente y eficiente, facilitando la integración de mayores cantidades de DER y energías renovables.

2. Metodología

El enfoque metodológico adoptado para este trabajo se divide en dos: el análisis de competitividad de los mercados utilizando el índice Herfindahl-Hirschman (HHI) y el desarrollo de modelos de regresión multivariante para evaluar la influencia y el impacto de distintas variables en los precios de los productos de flexibilidad.

El índice Herfindahl-Hirschman (HHI) es una herramienta estadística que permite medir la concentración de un mercado como la suma de los cuadrados de las cuotas de mercado de todos los proveedores. El HHI se emplea en este trabajo para examinar la estructura del mercado y la distribución del poder entre los agentes que operan en los mercados locales de servicios del sistema. La elección de este índice se justifica por su capacidad para cuantificar la competencia del mercado, permitiendo identificar si el mercado está dominado por unos pocos grandes proveedores o si, por el contrario, existe una distribución más equitativa entre muchos pequeños proveedores. En este estudio, se calcula el HHI a nivel general, por tipo de producto (Secure, Sustain, Dynamic y Restore) y por ubicación con el objetivo de proporcionar una visión clara y detallada de la competitividad en diferentes segmentos y ubicaciones.

Además, se utiliza la matriz de correlaciones para estudiar las relaciones de los precios de los productos de flexibilidad con un amplio conjunto de variables explicativas como son la tensión de conexión (kV), el proveedor, la tecnología, el número de ofertas recibidas, la capacidad flexible (MW) y el tiempo máximo de funcionamiento (hh:mm). La matriz de correlaciones es útil para visualizar la dirección y fortaleza de las relaciones lineales entre diversas variables. En el contexto del presente análisis, ayudará a encontrar correlaciones significativas que puedan afectar a los precios, sirviendo como base preliminar para la construcción de los modelos de regresión.

Los modelos de regresión lineal multivariante son una herramienta fundamental para cuantificar el efecto de las mencionadas variables independientes en el precio de los productos de flexibilidad. La utilidad de estos modelos recae en la posibilidad de estimar simultáneamente el efecto de diferentes variables sobre una variable dependiente continua. En este trabajo, se desarrollan diferentes modelos para cada tipo producto y para cada ubicación. Esta metodología permitirá identificar las variables más importantes que afectan a los precios y calcular de manera concluyente su influencia o impacto. Los modelos también ayudarán a entender las diferencias y variaciones en el impacto de estas variables en distintas ubicaciones, proporcionando así una visión completa de los factores determinantes en la formación de los precios en los mercados locales de servicios del sistema.

En definitiva, la metodología aquí planteada no solo permite caracterizar la competitividad del mercado y la distribución del poder entre los diferentes proveedores, sino que también permite comprender las dinámicas de precios a raíz de distintas características tanto técnicas como comerciales, hecho que sentará una base sólida para futuras investigaciones y desarrollo de políticas en el área de la gestión de la flexibilidad en sistemas eléctricos descentralizados.

3. Resultados

En este apartado, para el análisis de la competitividad de mercado, se utilizó el índice Herfindahl-Hirschman (HHI) para medir la concentración del mercado en los servicios de flexibilidad. Los resultados de la concentración de mercado revelaron un valor HHI general de 7237.84, indicando que el mercado está altamente concentrado y dominado por unos pocos grandes proveedores, siendo Octopus Energy el proveedor más dominante.

Por su parte, en los análisis por tipo de producto, se observaron grandes variaciones en los resultados. El producto Secure fue el único con un valor de HHI inferior a 2500, pues presentó un HHI de 2342.90, reflejando un mercado relativamente competitivo. El producto Sustain, sin embargo, con un HHI de 8490.91, mostró la mayor concentración, sugiriendo una muy fuerte presencia de unos pocos proveedores. Los productos Dynamic y Restore, por otro lado, presentaron índices HHI de 3155.56 y 3491.12, respectivamente, indicando nuevamente una alta concentración en estos productos.

El análisis por ubicaciones, además, reveló que la mayoría de las áreas estudiadas resultan extremadamente concentradas en términos de mercado, con 1278 ubicaciones registrando un HHI de 10000, lo que equivale a un monopolio absoluto, como se muestra en la Figura 2. Esta alta concentración refleja la falta de competencia en muchas áreas del mercado de servicios de flexibilidad, hecho que puede tener importantes consecuencias para la eficiencia del mercado y la equidad en los precios ofrecidos a los consumidores.

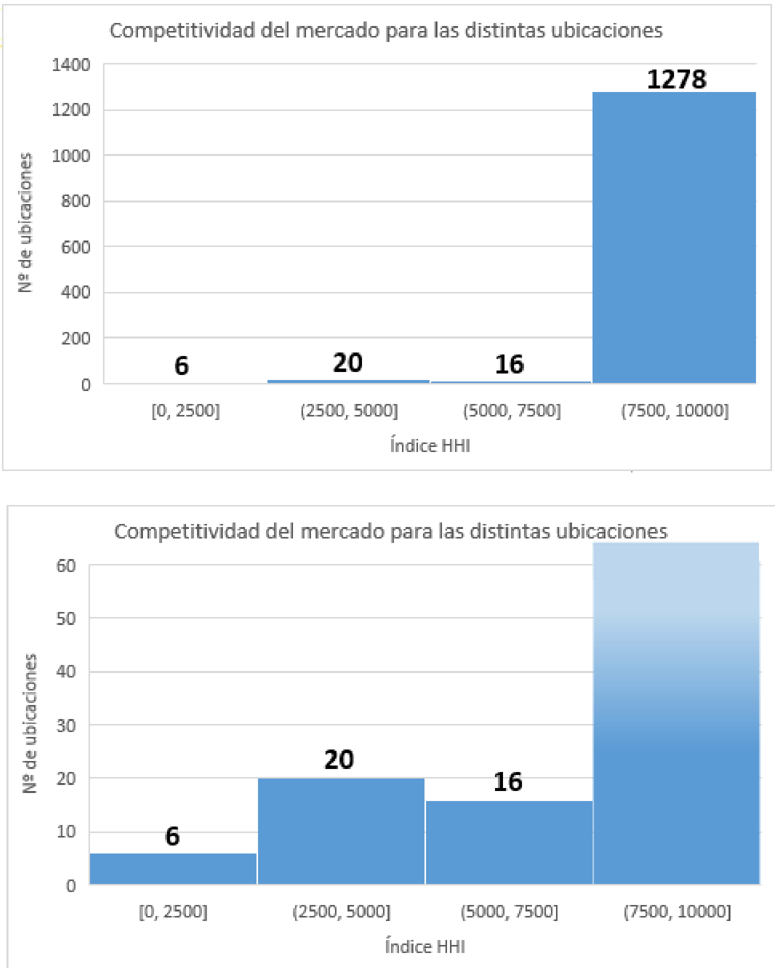

Figura 2: Competitividad del mercado para las distintas ubicaciones

En lo respectivo al estudio de los modelos de regresión, se examinó el efecto de distintas variables independientes (proveedor, tensión, tecnología, número de ofertas recibidas, capacidad flexible y tiempo máximo de funcionamiento) tanto en los precios de disponibilidad como de utilización para cada una de las ubicaciones disponibles y para aquellas ofertas que fueron aceptadas. Los resultados de los modelos se resumen en la Tabla 2 y en la Tabla 3, que muestran el número de lugares, en porcentaje, en los que la variable en cuestión tuvo mayor incidencia en el precio por tipo de producto.

Tabla 2: Número de ubicaciones (%) en las que la variable tuvo mayor impacto en el precio de disponibilidad por tipo de producto

Precio de disponibilidad €/MW/h	Proveedor	Tensión	Tecnología	Nº de ofertas recibidas	Capacidad flexible	Tiempo máximo de funcionamiento
Secure	76.25%	4.75%	0%	9.50%	4.75%	4.75%
Sustain	-	-	-	-	-	-
Dynamic	N	O	D	A	T	A
Restore	-	-	-	-	-	-

Tabla 3: Número de ubicaciones (%) en las que la variable tuvo mayor impacto en el precio de utilización por tipo de producto

Precio de utilización €/MWh	Proveedor	Tensión	Tecnología	Nº de ofertas recibidas	Capacidad flexible	Tiempo máximo de funcionamiento
Secure	63.75%	9%	4.50%	13.75%	4.50%	4.50%
Sustain	14.25%	14.25%	0%	14.25%	43%	14.25%
Dynamic	100%	0%	0%	0%	0%	0%
Restore	N	O	D	A	T	A

Para el caso del precio de disponibilidad, el proveedor fue la variable con mayor impacto en el precio en el 76.25% de las ubicaciones para el producto Secure, seguido por otras variables con menor influencia como es el caso del número de ofertas recibidas o la tensión. Para el resto de productos, no se pudieron obtener modelos de regresión por diferentes razones: en el caso de Sustain y Restore, porque los precios de disponibilidad son nulos para estos productos (no son remunerados por ello), y en el caso de Dynamic, debido a la insuficiencia de datos para obtener los modelos.

Para el caso del precio de utilización, el proveedor siguió siendo la variable con mayor impacto, especialmente en el caso del producto Dynamic, donde el análisis indicó una dependencia completa del proveedor, siendo esta la variable con mayor impacto en el 100% de las ubicaciones. El proveedor fue también la variable más determinante para el producto Secure, predominando en el 63.75% de las ubicaciones. El producto Sustain mostró un comportamiento diferente, siendo la variable más significativa la capacidad flexible en el 43% de las ubicaciones, hecho que destaca la importancia de esta variable en la determinación de los precios para este tipo de producto. Además, en este caso fue Restore el producto para el cual no se pudieron obtener los modelos de regresión debido a la insuficiencia de datos.

Estos resultados muestran la gran importancia que tienen los proveedores en la fijación de precios en los mercados de servicios de flexibilidad, así como la importancia de otras variables como la capacidad flexible en situaciones específicas. Además, se evidencia también la escasa competencia en diversas áreas del mercado, con altos niveles de concentración que podrían afectar tanto a la equidad como a la eficiencia en los precios de los servicios de flexibilidad proporcionados.

4. Conclusiones

Se destacan, en las conclusiones de este documento, varios puntos clave que se derivan del análisis realizado sobre los mercados locales de servicios del sistema. La investigación reveló una alta concentración en el mercado, implicando una importante falta de competencia, tal y como reveló el elevado valor del índice Herfindahl-Hirschman (HHI), tanto en el caso general como en el caso de varios productos y ubicaciones, principalmente en el producto Sustain y en numerosas regiones. Esta alta concentración del mercado sugiere la existencia de unos pocos grandes proveedores que dominan el mercado, lo que puede llevar a disminuir la innovación, aumentar los precios y reducir la eficiencia en la entrega de servicios de flexibilidad. Además, el hecho de depender de unos pocos proveedores puede hacer al sistema más vulnerable a interrupciones si un proveedor presenta dificultades técnicas o económicas.

Por su parte, los modelos de regresión multivariante desarrollados facilitaron la identificación de las variables más influyentes en los precios de disponibilidad y de utilización. Se observó que el proveedor es una variable crítica en la formación de precios, fundamentalmente en el caso de los productos Secure y Dynamic. La fuerte dependencia del proveedor refleja la necesidad de políticas y regulaciones que fomenten y promuevan un mercado más competitivo con más actores involucrados. El alto nivel de concentración y el dominio de ciertos proveedores podrían llevar a una posición de poder de mercado, pudiendo estos actores tener la capacidad de influir en la formación de precios de manera significativa.

Además, se identificó también la capacidad flexible como otro factor relevante en la formación de precios, especialmente para el producto Sustain (precio de utilización), lo que supone que la capacidad de los proveedores para ofrecer servicios de flexibilidad es valorada en el mercado, pudiendo así influir en los precios. Mediante las inversiones en infraestructura y tecnologías avanzadas se puede promover una mayor capacidad flexible, pudiendo ayudar así a mejorar la estabilidad del sistema eléctrico.

Las conclusiones generales del estudio resaltan la necesidad de diversificar los proveedores y reducir el poder de mercado de los principales actores. Para lograr tal objetivo, podrían implementarse políticas que favorezcan la entrada de nuevos actores y la diversificación de la oferta de los servicios de flexibilidad. Además, el despliegue de la infraestructura necesaria para incrementar la capacidad flexible disponible puede ayudar también a estabilizar y reducir los precios, beneficiando tanto a los consumidores finales como a los operadores del sistema eléctrico.

En resumen, este trabajo permite destapar los desafíos y oportunidades que actualmente prevalecen en los mercados locales de servicios del sistema, destacando la necesidad de promover un mercado más competitivo, eficiente y sostenible. Las recomendaciones derivadas de estos resultados podrían servir de base para futuras políticas y estrategias que fomenten la transición hacia un sistema eléctrico más resiliente y equitativo.

5. Bibliografía

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ANALYSIS OF EXISTING LOCAL MARKETS FOR SYSTEM SERVICES, PRODUCT PRICING AND AGENT´S PARTICIPATION

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ABSTRACT

1. Introduction

The electricity system is in a period of great transformation, with the increasing penetration of distributed energy resources (DER) and the transition to a more decentralized electricity system. The transformation is key to achieving greater gains in sustainability, resilience and operational efficiency in the power system, as well as increasing the penetration of renewables in the energy mix. Historically, power grids have been centralized, with large power generation plants supplying electricity along the transmission and distribution infrastructure. However, with the advancement of renewable energy technology and distributed resource technology, such as solar and wind energy through panels and turbines, respectively, this centralized configuration is evolving into a more distributed system. Figure 1 shows this transformation of the structure of the electrical system [1].

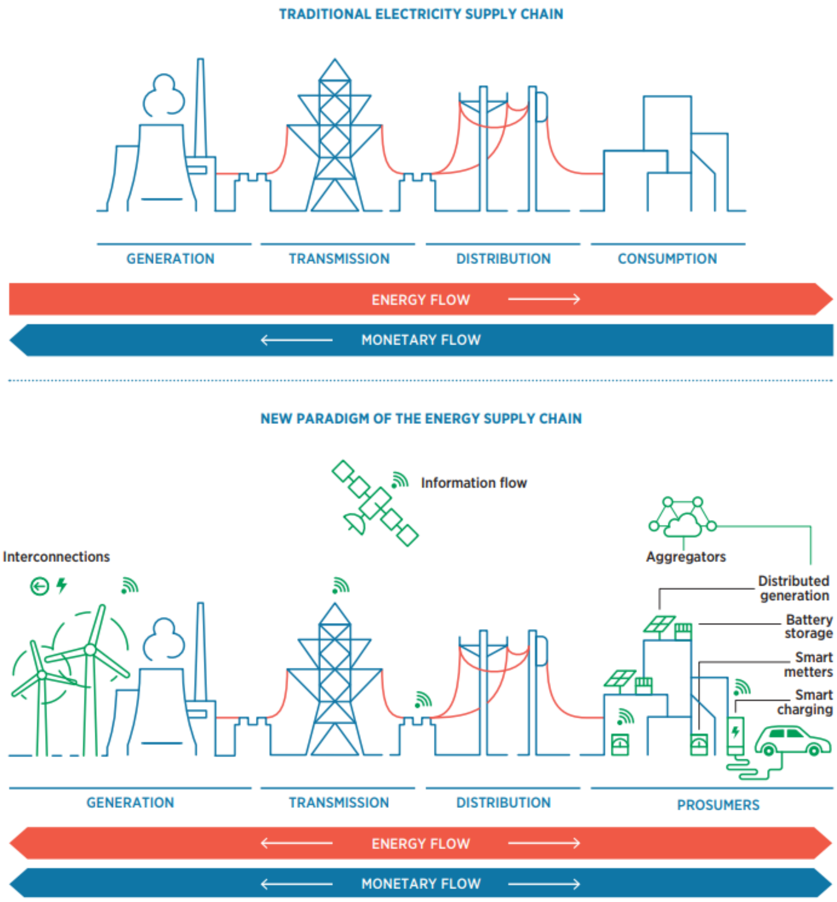

Figure 1: Transformation of the electricity system structure [1]

The decentralization of the electricity system promotes the participation of a greater number of different actors, both in energy generation and consumption, generating a more dynamic and adaptable system to the variability in energy demand and supply. This adaptability, understood as flexibility, has become a fundamental issue for maintaining system stability, mainly with the incorporation of renewable sources with variable and intermittent generation [2].

In this sense, local markets for system services represent a fundamental tool to deal with the growing complexity of the electricity system. Through these markets, DERs are enabled to provide important services for the system, such as frequency regulation, voltage control and operating reserves, through an energy exchange that is tailored to the needs of the system. Local market platforms allow an interaction between flexibility service providers and system operators, through which the negotiation of services can be performed in an efficient and transparent manner.

The aim of this thesis is to analyze local markets for system services, with a special interest in flexibility markets in the UK through the Piclo platform. For this purpose, different flexibility products have been studied: Secure, Sustain, Dynamic and Restore, products that are remunerated both by availability (in the cases of Secure and Dynamic) and by utilisation (in all cases), identifying differences in price formation and between market areas. Thus, several variables have been considered, such as location, technology, supplier and voltage, among others, to better understand price formation and the behavior of participants in these markets. A more detailed summary of the characteristics of the products studied is shown in Table 1.

Table 1: Characteristics of the different flexibility products [3]

	Use Case	**Availability £/MW/h**	**Utilisation £/MWh**	**Objective**
Secure	Pre-fault	Yes, Payment	Yes, Payment	Aims to resolve operational constraints (peak shaving)
Sustain	Scheduled	No	Yes, Payment	Aims to address scheduled forecast overload
Dynamic	Post-fault	It depends on DSO	Yes, Payment	Aims in network abnormality or in planned outage
Restore	Post-fault grid restoration	No	Yes, Payment	Aims to restore the network

This research project seeks to fill a gap in the understanding of emerging system services markets by conducting a comprehensive analysis of the various factors that affect and influence both price formation and participant behavior. The information gathered through this research will contribute to the development of a more sustainable, resilient and efficient electricity system, facilitating the integration of greater amounts of DER and renewable energy.

2. Methodology

The methodological approach adopted for this work is divided into two: the analysis of market competitiveness using the Herfindahl-Hirschman Index (HHI) and the development of multivariate regression models to evaluate the influence and impact of different variables on the prices of flexibility products.

The Herfindahl-Hirschman Index (HHI) is a statistical tool to measure the concentration of a market as the sum of the squares of the market shares of all suppliers. The HHI is used in this paper to examine the market structure and the distribution of power among the agents operating in the local service markets of the system. The choice of this index is justified by its ability to quantify market competition, making it possible to identify whether the market is dominated by a few large providers or whether, on the contrary, there is a more equal distribution among many small providers. In this study, the HHI is calculated at the overall level, by product type (Secure, Sustain, Dynamic and Restore) and by location with the objective of providing a clear and detailed view of the competitiveness in different segments and locations.

In addition, the correlation matrix is used to study the relationships of flexibility product prices with a wide set of explanatory variables such as connection voltage (kV), provider, technology, number of bids received, flexible capacity (MW) and maximum run time (hh:mm). The correlation matrix is useful to visualize the direction and strength of linear relationships between various variables. In the context of the present analysis, it helps to find significant correlations that may affect prices, serving as a preliminary basis for the construction of the regression models.

Multivariate linear regression models are a fundamental tool for quantifying the effect of the aforementioned independent variables on the price of flexibility products. The usefulness of these models lies in the possibility of estimating simultaneously the effect of different variables on a continuous dependent variable. In this work, different models are developed for each type of product and for each location. This methodology makes it possible to identify the most important variables affecting prices and conclusively estimate their influence or impact. The models also help to understand the differences and variations in the impact of these variables in different locations, thus providing a complete picture of the determinants of price formation in the system's local service markets.

In short, the methodology proposed here not only characterizes market competitiveness and the distribution of power among different providers, but also provides an understanding of the price dynamics resulting from different technical and commercial characteristics, which will lay a solid foundation for future research and policy development in the area of flexibility management in decentralized electricity systems.

3. Analysis of results

In this section, for the analysis of market competitiveness, the Herfindahl-Hirschman Index (HHI) was used to measure market concentration in flexibility services. The results of the market concentration revealed an overall HHI value of 7237.84, indicating that the market is highly concentrated and dominated by a few large providers, with Octopus Energy being the most dominant one.

In the analysis by product type, large variations in the results were observed. The Secure product was the only one with an HHI value below 2500, with an HHI of 2342.90, reflecting a relatively competitive market. The Sustain product, however, with an HHI of 8490.91, showed the highest concentration, suggesting a very strong presence of a few providers. The Dynamic and Restore products, on the other hand, showed HHI indices of 3155.56 and 3491.12, respectively, again indicating a high concentration in these products.

The analysis by location also revealed that most of the areas studied are extremely concentrated in terms of market share, with 1278 locations registering an HHI of 10000, which is equivalent to an absolute monopoly, as shown in Figure 2. This high concentration reflects the lack of competition in many areas of the flexibility services market, a fact that may have important consequences for market efficiency and fairness in the prices offered to consumers.

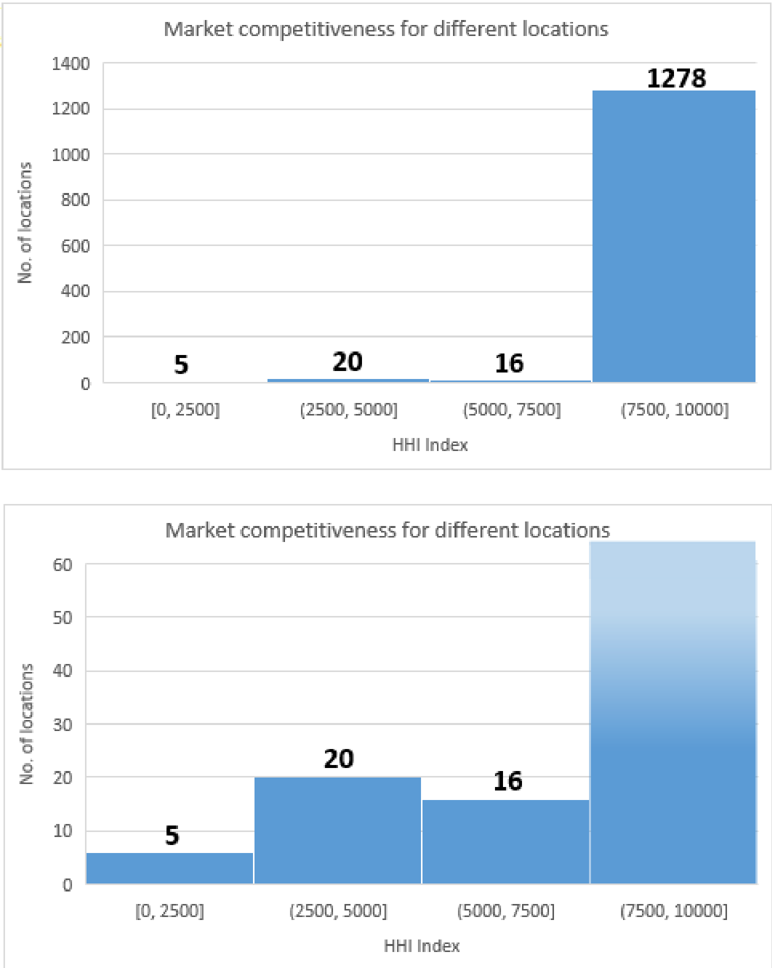

Figure 2: Market competitiveness for different locations

The regression models examined the effect of different independent variables (provider, voltage, technology, number of bids received, flexible capacity and maximum run time) on both availability and utilisation prices for each of the available locations and for those bids that were accepted. The results of the models are summarized in Table 2 and Table 3, which show the number of locations, in percentage, where the variable in question had the greatest impact on price by product type.

Table 2: No. of locations (%) in which the variable had the greatest impact on availability price by product type

Availability Price €/MW/h	Provider	Voltage	Technology	No. of bids received	Flexible Capacity	Maximum Run Time
Secure	76.25%	4.75%	0%	9.50%	4.75%	4.75%
Sustain	-	-	-	-	-	-
Dynamic	N	O	D	A	T	A
Restore	-	-	-	-	-	-

Table 3: No. of locations (%) in which the variable had the greatest impact on utilisation price by product type

Utilisation Price €/MWh	Provider	Voltage	Technology	No. of bids received	Flexible Capacity	Maximum Run Time
Secure	63.75%	9%	4.50%	13.75%	4.50%	4.50%
Sustain	14.25%	14.25%	0%	14.25%	43%	14.25%
Dynamic	100%	0%	0%	0%	0%	0%
Restore	N	O	D	A	T	A

In the case of the availability price, the provider was the variable with the greatest impact on the price in 76.25% of the locations for the Secure product, followed by other variables with less influence, such as the number of bids received or the voltage. For the rest of the products, regression models could not be obtained for different reasons: in the case of Sustain and Restore, because the availability prices are null for these products (they are not remunerated for it), and in the case of Dynamic, due to insufficient data to obtain the models.

For the case of utilisation price, the provider continued to be the variable with the greatest impact, especially in the case of the Dynamic product, where the analysis indicated a complete dependence on the provider, this being the variable with the greatest impact in 100% of the locations. The provider was also the most determinant variable for the Secure product, predominating in 63.75% of the locations. The Sustain product showed a different behavior, with the most significant variable being the flexible capacity in 43% of the locations, a fact that highlights the importance of this variable in determining prices for this type of product. Furthermore, in this case Restore was the product for which regression models could not be obtained due to insufficient data.

These results show the great importance of providers in pricing in flexibility services markets, as well as the importance of other variables such as flexible capacity in specific situations. In addition, there is also evidence of weak competition in several areas of the market, with high levels of concentration that could affect both fairness and efficiency in the pricing of the flexibility services provided.

4. Conclusions

The conclusions of this document highlight several key points derived from the analysis conducted on the local service markets of the system. The investigation revealed a high concentration in the market, implying a significant lack of competition, as revealed by the high value of the Herfindahl-Hirschman Index (HHI), both in the general case and in the case of several products and locations, mainly in the Sustain product and in numerous regions. This high market concentration suggests the existence of a few large providers dominating the market, which can lead to decreased innovation, higher prices and reduced efficiency in the delivery of flexibility services. In addition, reliance on a few providers may make the system more vulnerable to disruption if a provider encounters technical or economic difficulties.

In turn, the multivariate regression models developed facilitated the identification of the most influential variables in availability and utilisation prices. It was observed that the provider is a critical variable in price formation, fundamentally in the case of Secure and Dynamic products. The strong dependence on the provider reflects the need for policies and regulations that encourage and promote a more competitive market with more players involved. The high level of concentration and the dominance of certain providers could lead to a position of market power, and these players may have the ability to influence price formation significantly.

In addition, flexible capacity was also identified as another relevant factor in price formation, especially for the Sustain product (utilisation price), which implies that the ability of providers to offer flexible services is valued in the market, thus being able to influence prices. Investments in infrastructure and advanced technologies can promote greater flexible capacity, which can help to improve the stability of the electricity system.

The overall conclusions of the study highlight the need to diversify providers and reduce the market power of the main players. To achieve this goal, policies that favor the entry of new players and the diversification of the supply of flexibility services could be implemented. In addition, the deployment of the necessary infrastructure to increase the available flexible capacity can also help to stabilize and reduce prices, benefiting both end-consumers and electricity system operators.

In summary, this work uncovers the challenges and opportunities currently prevailing in local system services markets, highlighting the need to promote a more competitive, efficient and sustainable market. The recommendations derived from these results could serve as a basis for future policies and strategies to foster the transition towards a more resilient and equitable electricity system.

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1. Introduction

The electric industry is in a disruptive stage with the increased penetration of distributed energy resources (DER) and the trajectory towards a more distributed electric system. This disruption is a paradigm shift in both the sustainability, resilience and operational efficiency of the power system and the penetration of renewables. Local markets for system services are an innovative concept to manage congestions in distribution networks and to meet the demand for services in an efficient and reliable manner.

Traditionally, electricity systems have existed in a decentralized form, with electricity generation performed in large-scale plants and served to end customers through the transmission and distribution grid. However, this trend is changing with the advent of renewable and DER technologies, such as solar panels, wind turbines and energy storage systems, which tend to be distributed rather than centralized system. The distributed nature allows incorporating more actors along the energy generation and consumption value chain and, as such, would tend to have a more dynamic and adaptive energy system. Figure 1 shows this transformation of the structure of the electrical system [1].

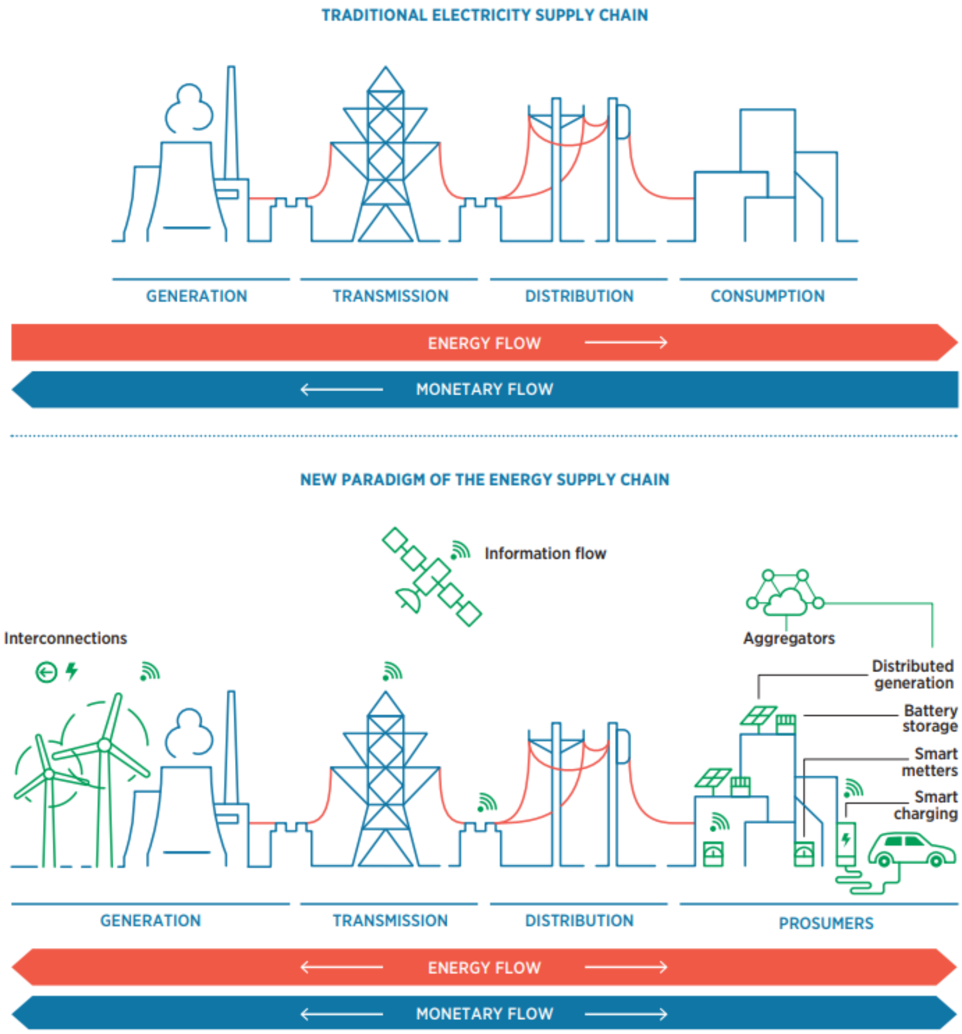

Figure 1: Transformation of the electricity system structure [1]

However, the penetration of a more distributed grid and the introduction of renewables into the mix also have their own challenges. These include managing the variability and intermittency of renewable sources, the need for new grid infrastructure, and creating markets that can effectively aggregate these distributed resources. Power system flexibility, or the ability to change electricity production or consumption in response to market signals, has thus become a critical component in achieving system stability and efficiency [2].

Within this framework, local markets for system services will allow DERs to actively participate and provide important services such as frequency regulation, voltage control, and operating reserves. These markets facilitate the provision of services by regulating electricity exchanges to meet system operational needs. Specifically, flexibility markets allow DERs to engage in flexibility transactions to help restore balance and support electric system optimization.

The research of local system services markets is therefore the main focus of this paper, focusing largely on flex markets in the UK. This study focus on several Piclo flexibility products (Secure, Sustain, Restore and Dynamic), as well as an analysis of a set of variables, including location, technology, suppliers or voltage, with the purpose of providing information on the price formation and dynamics of participants in these markets. In addition, the relationships between product characteristics and prices are analyzed, as well as the differences between markets and technologies adopted.

For this purpose, the analysis is performed using data provided by the Piclo platform, a flexibility market solution in the UK. Advanced statistical methods, including multivariate regression analysis, are used to determine the impact of several variables on the price of flexibility products. A study is also conducted to assess the competitiveness of the market through the Herfindahl-Hirschman Index (HHI), both overall and locally.

Thus, the main objectives of this work are the following ones:

- Evaluate market competitiveness.
- Study the correlations between price and the characteristics of the different products.
- Evaluate price differences between locations.
- Identify gaps and distortions in local market mechanisms and provide recommendations to overcome them.

Moreover, Piclo Flex is one of the tools that enable interaction between flexibility service providers and system operators, through an interface that provides access to a transparent and efficient marketplace for exchanging services. Figure 2 shows an image of this platform. The scope of the tool includes the participation of a wide range of players, from distributed generators and active consumers to aggregators of flexibility resources [3].

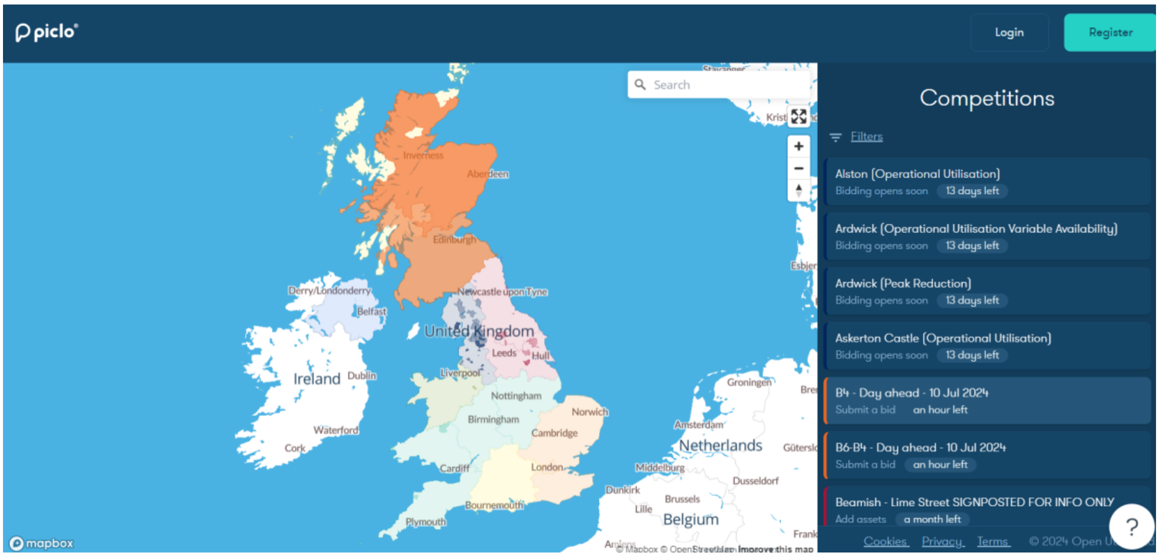

Figure 2: Piclo's platform [4]

This study expands and improves knowledge of the system's service markets at the local level, as well as provides important information to operators, regulators and other market players. By identifying pricing variables and looking for regional and technological differences, this research helps to support the development of more efficient and fairer market mechanisms. In addition, certain distortions are identified when investigating market competitiveness and recommendations are made to improve efficiency and transparency in these emerging markets.

Ultimately, the move toward a more decentralized and flexible electric grid is a major concern in addressing current and future challenges in the electric industry. Local system service markets are one of the most important parts of achieving greater penetration of DERs and achieving greater efficiency in power system operation. This project closes a large knowledge gap on such markets and, through a detailed study, identifies the factors underlying the price formation dynamics and the behavior of the actors. The results of this work enable the development of market mechanisms towards a more sustainable, resilient and efficient electricity system.

2. State of the art

2.1 Evolution of the electrical system

The development of the electricity system has been going through a series of technological and structural transformations through which there has been a change in the electricity generation, transmission and distribution scenario. This paper describes this development in the following three sections, namely, the transition from centralized to decentralized systems, the integration of renewable energies and distributed energy resources, and the challenges in system operation with high penetration of renewables.

2.1.1 Transition from centralized to decentralized systems

As mentioned above, electricity grids have followed a centralized model where electricity generation occurred in large plants, generally located at long distances from consumption points. Electricity was then transmitted using a high-voltage grid and distributed to consumers through low-voltage grids. While this centralized approach had benefits in terms of economies of scale and centralized control, it was also exposed to potential catastrophic failures and limitations in its ability to incorporate distributed resources [1].

However, over the course of the last few decades there has been a shift towards a more distributed power grid. This transformation has been made possible for a number of reasons, including technological advancement, the decreasing cost of renewable technologies, and the growing demand for sustainability and resilience. In a decentralized system, power generation is carried out at local locations close to the point of consumption with many distributed energy resources including solar panels, wind turbines, energy storage systems, and backup generators. This architecture allows for greater flexibility and resilience of the electrical infrastructure, as distributed energy is able to adjust more quickly in response to imbalances between energy supply and demand [5].

2.1.2 Integration of renewable energies and distributed energy resources

One of the main driving forces behind the shift towards the more distributed nature of electricity grids has been the spread of renewables and distributed energy sources. Renewable energies, such as solar and wind, have expanded rapidly as their costs have fallen and thanks also to supportive policies put in place by governments around the world. Figure 3 shows this increase in renewable energies globally over the last decades. These energy sources are sustainable and environmentally friendly, but they also present their challenges due to their variability and intermittency [6].

Figure 3: Expansion of renewable energies globally from 1965 to 2023 [7]

These energy sources can be effectively managed with the development of grid management and energy storage technology. Excess renewable energy can be stored when not much is needed and released for use when there is high demand or low renewable generation, using storage systems such as lithium-ion batteries. In addition, smart grids use information and communication systems that enable real-time monitoring and control of electricity flow for the purpose of increasing system efficiency and reliability [8].

DERs also include other technologies such as demand response, through which energy consumption is adjusted based on signals in the market by consumers, and distributed generation, through which electricity is generated locally by small generators. Such resources result in an electricity system with greater flexibility and contribute to the stability and operational efficiency of the system [9]

2.1.3 Challenges in system operation with high penetration of renewables

A high penetration of renewable energy and distributed energy resources into the electric grid presents a list of operational challenges. One of the most important is the problem of controlling the variability and intermittency that is naturally inherent in renewable energy sources. As already mentioned, wind and solar power are intermittent and dependent on different weather conditions, so their output can change drastically. For example, Figure 4 shows the variability of these generation sources in Spain in 2021. In order to have synchronization between electricity demand and supply, there must be a dynamic infrastructure that is able to keep pace with these changes in a timely manner [2].

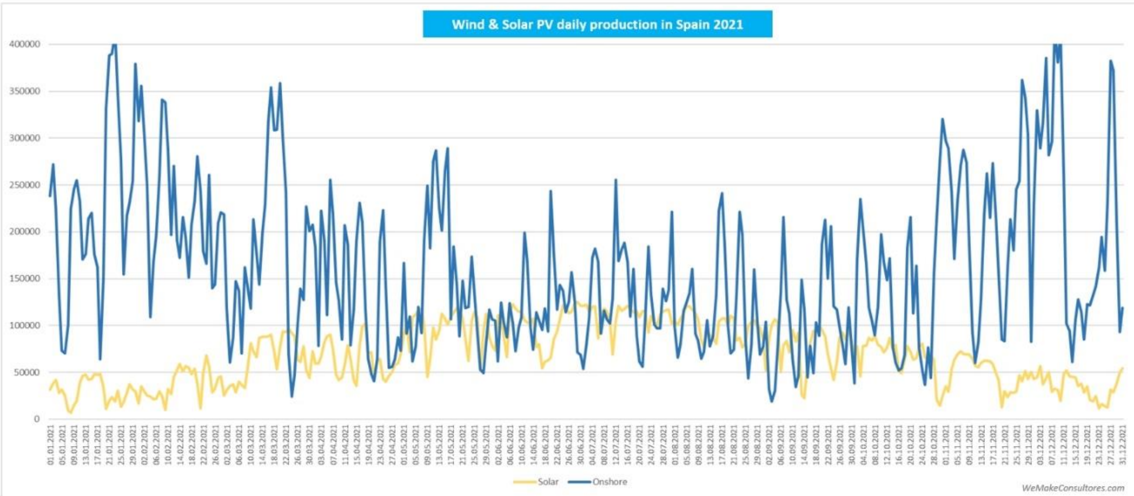

Figure 4: Wind & Solar PV daily production variability in Spain in 2021 [10]

Another key challenge is the implementation of high amounts of distributed generation in the distribution grid. Conventional distribution networks were originally not built to support the bi-directional transmission of electricity coming from distributed generation. This implies both the incorporation of new grid management technologies and the modernization of the distribution infrastructure to support these flows effectively [11]

In addition, the high penetration of renewables also has the potential to affect the quality and stability of electricity supply. Variations in generation can result in variations in system frequency and voltage, a fact that could adversely affect sensitive devices as well as overall system performance. To compensate for such effects, advanced control equipment and reactive compensation devices are used to stabilize the system [12]

Finally, the evolution of the system as a whole towards a more decentralized approach and with a high penetration of renewables also implies the need for reforms in electricity markets and regulatory paradigms. New business models and market mechanisms are needed to encourage participation of distributed energy resources and ensure fair and effective compensation for the flexibility services provided. This includes implementing local flexibility markets and adopting dynamic tariff structures that realistically reflect system conditions [13]

2.2. Concept of flexibility in the electric system

The flexibility of the electricity system is a fundamental issue to ensure a strong and efficient grid, especially in an environment of increased penetration of renewable energies and distributed energy resources. The following is a definition of this concept and the different types of flexibility, as well as its main resources: generation, demand and storage.

2.2.1 Definition and types of flexibility

Flexibility in the power system refers to the property of the system to react to variability in electricity generation and demand in real time, in an effort to achieve balance and stability in grid operation. This is an essential property of the system in order to accommodate a large amount of renewable energy, which by nature is intermittent and fluctuating due to its dependence on weather [14]

There are a variety of flexibilities in the power system, which can be classified according to the response time and the nature of the required performance:

- **Short-term flexibility**: This refers to the ability to adapt to immediate and fluctuating variations in generation and demand, usually on time scales of a few seconds to minutes. This is the type of flexibility critical for voltage regulation and frequency matching. For example, a solar plant's power generation when a cloud passes over it can drop drastically, so the system must adjust quickly to counteract this type of situation. In this regard, fast-response plants in terms of energy, such as natural gas and batteries, are quite critical [15]

- **Medium-term flexibility**: This refers to the ability to adjust to variations that occur in electricity generation and demand over a period of hours. This type of flexibility is essential to handle the daily fluctuation in the availability of renewable energy sources and in the daily demand for electricity. For example, solar power generation is highest throughout the day and decreases in the evening. For its part, energy demand tends to be higher in the afternoon-evening. Available storage and various flexible power plants can help smooth these daily variations [15]

- **Long-term flexibility**: This refers to the ability to adjust, again, generation and demand, in this case over days, weeks or even seasons. This flexibility is key to deal with long periods of high or low renewable generation, and to deal with schedules in generation and storage capacity. For example, in the case of low wind generation over a period of weeks, other energy supplies and long-term storage would have to make up the shortfall [15]

2.2.2 Sources of flexibility: generation, demand, storage

Flexibility in the electricity system can be provided by different types of sources, each with different characteristics and capacities.

2.2.2.1 Generation

Flexible generation is defined as the ability of generating plants to change their level of electricity generation to respond to different market signals or to meet different system needs. Some of these plants, such as hydroelectric or natural gas plants, are flexible because they are able to quickly scale and adjust their output. They can be turned on and off quickly, and regulate their output according to system demand, which is critical to counteract the variability of renewable generation [15]

Hydroelectric plants, and particularly pumped-storage plants, have significant flexibility. During hours when demand is low, extra electricity is used to pump water to an elevated reservoir. This is released for generation when demand is high, creating an agile and efficient response to system demands. Figure 5 explains the operation of these plants in more detail. In addition, natural gas plants can operate in base load mode, or also, in peak generator mode, with good and fast response times [15]

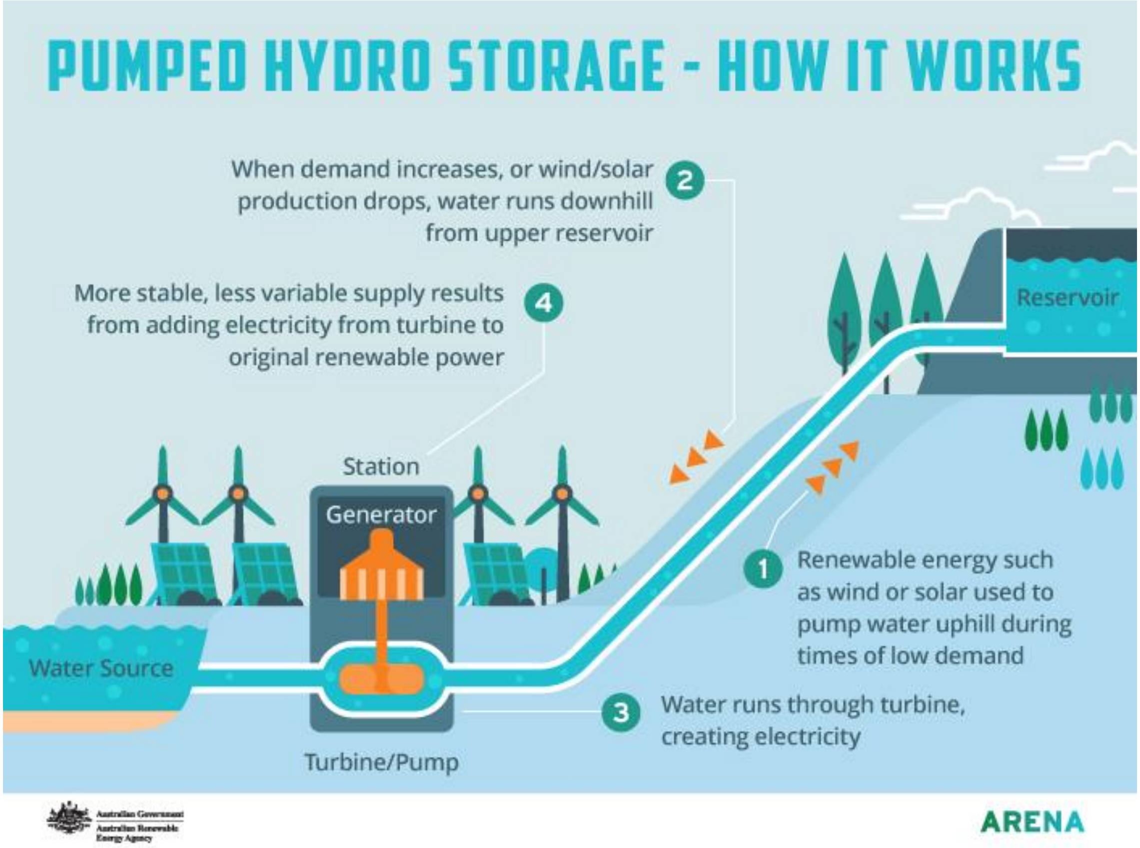

Figure 5: Operation of a pumped-storage hydroelectric power plant [16]

In addition, renewable energy plants, such as solar and wind power plants, can also be used to enable system flexibility through methods such as curtailment, i.e., by intentionally reducing production, and through the use of hybrid energy systems that combine renewable energy generation with energy storage. In the event of overproduction, for example, on a very sunny or windy day, the generation of such plants can also be intentionally controlled and limited so that the balance of the system is maintained [17]

2.2.2.2 Demand

Demand can also be an important source of flexibility through response, i.e., changing the electricity usage behavior of end consumers in response to market signals or in response to system needs. Demand response programs can be encouraged through active tariffs, service contracts, and other demand management techniques. Such programs help consumers reduce electricity consumption at times of high demand (as shown in Figure 6) or increase this consumption in situations of excess renewable energy [18].

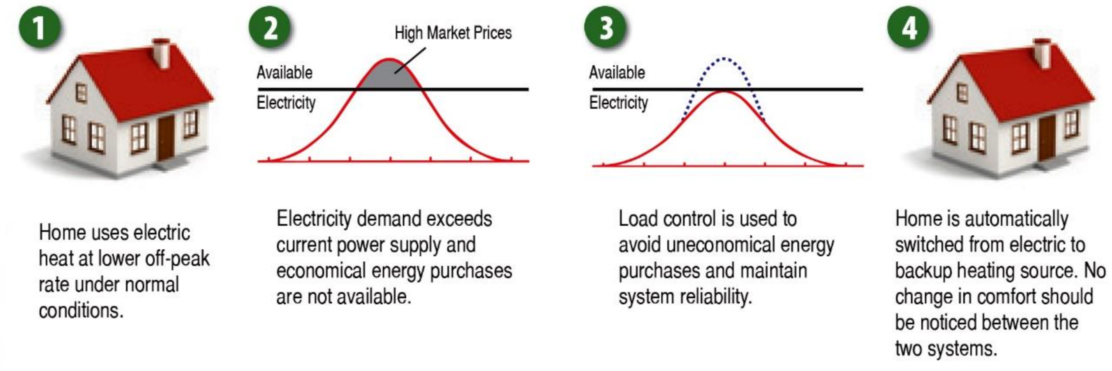

Figure 6: Example of demand response in a household [19]

For example, industrial, commercial and residential consumers can be part of these programs, varying their consumption depending on the price of electricity or a particular incentive that is in compensation for reduced demand during peak periods or when renewable energy generation is low. For instance, a factory manager would schedule some of the energy-intensive activities during hours when there is low demand or low electricity prices. Similarly, households can also adjust the use of energy-consuming appliances, such as washing machines and dryers, in response to price signals [20].

The application of smart technologies, particularly residential automation systems and smart meters, facilitates the ability of consumers to participate in demand response programs. These technologies allow consumers to monitor their electricity consumption and automatically respond to real-time pricing based on market conditions through electricity load management [20].

2.2.2.3 Storage

Energy storage is one of the main contributions to flexibility in the power system. Energy storage systems, such as lithium-ion batteries, pumped hydro and other energy storage technologies, store surplus generation when demand is low, and discharge this energy when demand is high or generation is lower. These resources not only balance demand with supply in the short term, but also provide important ancillary services [21].

Of the storage technologies, lithium-ion batteries are well suited for frequency regulation and immediate response to generation and demand variability. They are able to charge and discharge rapidly and respond almost instantaneously to system requirements. Figure 7 illustrates the operation of this type of batteries. In contrast, pumped hydro provides very high long-term storage, which is essential to accommodate the seasonal variability of renewable generation [21].

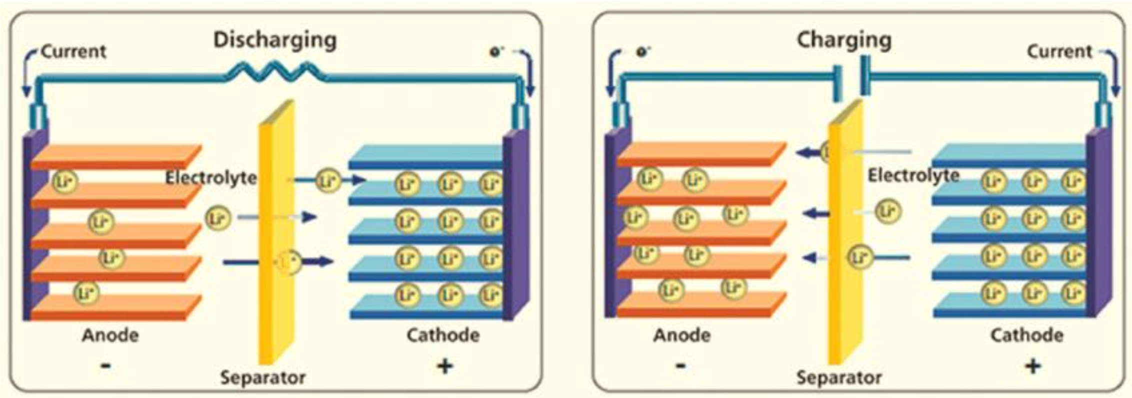

Figure 7: Basic working principle of a lithium-ion battery [22]

In addition, energy storage enables higher penetration of renewable energy sources by smoothing generation variabilities and keeping power supply stable. For example, if wind generation at night is high, when demand is low, excess electricity can be stored in batteries or pumped hydro and made available at peak hours during the day when demand is high [21].

The resilience of the power system can also be enhanced by storage through the provision of backup power in conditions such as power outages or emergencies. For areas with unstable or unreliable power systems, storage systems can provide a stable and continuous supply of power to improve system security and stability [21].

2.3. Local markets for system services

Local system service markets are an emerging in the contemporary electricity system. A definition and objectives of local system service markets, the types of agents participating in these markets, barriers and opportunities for participation, differences from traditional wholesale markets, potential benefits, and a detailed description of the products studied in this paper are provided in this section.

2.3.1 Definition and objectives

Local system service markets are an important innovation to address the increasing complexity of the modern electricity system. Local system service markets provide a platform where distributed energy resources and renewables can work together to provide services critical to the stabilization and efficient operation of the power grid. The services provided in such markets include frequency regulation, voltage control, operating reserve, congestion management, and other ancillary services that together balance electricity supply and demand in real time [23].

The main goals that local markets for system services pursue are diverse and ambitious. First, they seek to maximize efficiency in the operation of the electric grid. By allowing distributed energy resources to contribute to the provision of system services, the utilization of existing resources is maximized and costly investments in large infrastructure are reduced. In addition, these markets facilitate the penetration of a higher percentage of renewable energies, through mechanisms that address their variability and intermittency. Another fundamental objective is to improve the resilience of the electricity system since, with the introduction of distributed energy resources, local and more immediate resilience to any contingency is possible. Finally, local markets for system services promote the active participation of consumers, including prosumers or consumers who also produce energy, who are able to bring flexibility and responsiveness to the grid [24]

2.3.2 Types of agents

In the local markets for system services, there are several types of agents with different roles:

- **Producers:** they can be centralized or distributed producers. Distributed producers, such as rooftop solar plants or small wind turbines, can make their generation capacity available to the system.

- **Consumers**: Consumers can actively participate in such markets through demand response programs, so that their consumption is guided by the market price signal.

- **Prosumers**: Prosumers are consumers who also produce electricity, usually in the form of solar panels installed at their residence or commercial facility, and can sell excess electricity generated to the grid. Figure 8 illustrates this difference between consumer and prosumer.

- **Aggregators**: They perform the function of intermediaries by taking a group of DERs and coordinating their presence in the market in order to provide system services in a coordinated and efficient manner [1].

- **Market operator:** The market operator is responsible for the organization and management of the system's local service markets. It ensures efficient and fair market operation by adjusting supply and demand while maintaining system reliability. The market operator is also responsible for overseeing the bidding process, determining market clearing prices and ensuring compliance with regulatory requirements.

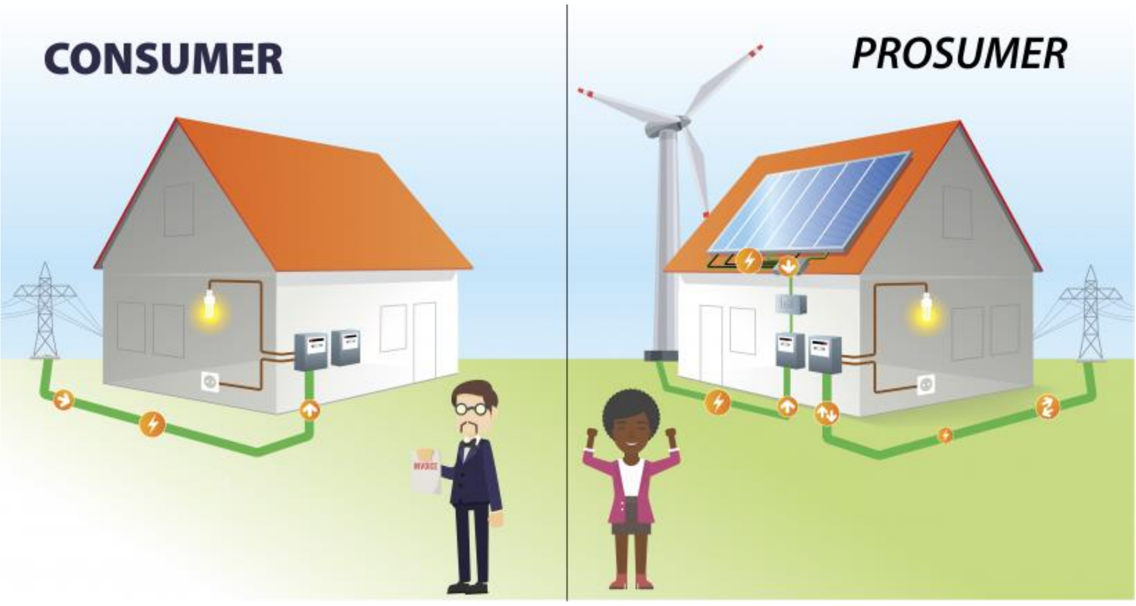

Figure 8: Consumer vs prosumer [25]

2.3.3 Barriers and opportunities for participation

Participation in local markets for system services presents a number of barriers and opportunities that require attention to ensure the success of these new emerging markets. Among the most significant barriers are existing rules and policies, which are not yet well adapted in many cases to facilitate the participation of DERs in local markets. In addition, the technologies and infrastructure needed to manage and integrate DERs are often not well developed. These include network infrastructure and communication technologies. Another major barrier is the lack of knowledge and technical capacity among DER owners and other stakeholders, which can both reduce and limit their effective participation [26]

However, despite the barriers posed, there are also several opportunities. Continuing technological innovations in energy storage, smart grids, and energy management systems are paving the way for greater penetration of DERs. Not only do they provide greater dimensions of responsiveness and flexibility to the power system, but they also reduce associated costs, including operational costs by optimizing resource use, investment costs through economies of scale, integration costs by facilitating the seamless incorporation of DERs into existing infrastructure, maintenance costs due to improved detection and prevention mechanisms, and social and environmental costs by reducing the reliance on non-renewable energy sources. In addition, local markets can offer DER owners and other participants promising new sources of revenue in the form of high economic returns as an incentive. The growing demands for sustainable and resilient solutions also contribute to the creation and development of these markets, creating opportunities for greener and more resilient power system planning [27].

2.3.4 Differences with traditional wholesale markets

Local system services markets differ significantly from traditional wholesale markets. In terms of size and scope, wholesale markets operate on a large scale, buying and selling large volumes of energy on both a regional and national level. Local markets, on the other hand, serve much smaller and more specific geographic areas, resulting in much more precise management tailored to local needs. This size and scale contrasts with wholesale markets, allowing them to offer greater agility and responsiveness to the demands and contingencies of the electricity system [28].

Another significant contrast comes from the role of DERs. While traditional wholesale markets have been dominated by large-scale grid-connected plants, local markets are specifically designed to link and control DERs. This encompasses assets such as rooftop solar plants, small-scale wind turbines and other distributed generators. The structure of the local markets facilitates rapid and flexible response to system requests by making use of the rapid responsiveness of DERs and demand response programs. This responsiveness is necessary to manage the variability and intermittency of renewables in order to maintain power system stability.

2.3.5 Potential benefits for the electricity system and market participants

Local markets for system services present a host of potential benefits that can completely change the efficiency and behavior of the electricity system. One of the most important benefits is increased operational efficiency. By incorporating DERs and implementing demand response capability, local markets can reduce infrastructure investment and minimize losses in both the distribution and transmission process. All of this results in optimizing resource availability and reducing the operating costs of the electricity system.

Apart from the benefit of operational efficiency, these markets allow the penetration of a higher proportion of renewable energies. By being able to handle the variability and intermittency of renewables, local markets can increase the share of green energy in the energy mix, resulting in a contribution to environmental sustainability. Due to the flexibility and rapid responsiveness of DERs, renewable energy resources can be incorporated in a greater proportion into the grid without compromising system stability.

Among the other benefits is active consumer participation. Local markets allow consumers and prosumers to actively participate in the electricity market, offering both their generation capacity and demand response capabilities. This participation contributes flexibility and responsiveness to the system, while at the same time it creates revenue opportunities for participants. By empowering the consumer and allowing them to play a direct role in the stability and efficiency of the electricity system, local markets foster higher levels of engagement and awareness about energy use [27]

2.4. Local market platforms

The system's local service markets use technological platforms that allow the various market players to interact with each other. In addition, these platforms also manage service offers and demands, and ensure an efficient and transparent operation. In the following, the Piclo platform is explained and described in detail. Other important existing platforms are also briefly described, such as GOPACS in the Netherlands or NODES in Norway.

2.4.1 Detailed description of Piclo

Piclo is one of the UK's leading platforms for delivering flexibility services in local markets. A platform founded in 2013, Piclo Flex has expanded to become a solution capable of integrating a wide range of electricity market participants, from consumers and prosumers to distributed generators and aggregators. The platform enables these different players to bid and demand flexibility services, allowing electricity supply and demand to be managed in real time, helping to balance the two and reinforcing grid stability [3].

Piclo Flex functions as an online marketplace in which distribution system operators (DSOs) can reflect their different flexibility needs, and different flexibility service providers can bid accordingly. The system manages the dynamics of the auctions, ensures price transparency, and enables the contracting and settlement of the services provided. The flexibility solutions offered with Piclo include the Secure, Sustain, Dynamic, and Restore products, each of which is suited to meet different operational requirements of the power grid [29].

Among Piclo's outstanding advantages are both its accessibility and ease of use. The software has a very user-friendly interface with intuitive tools and robust back-end support to guide its users. Piclo has also focused on continuous improvement, by adapting to the changing needs of the industry, and by integrating new technologies.

2.4.2 Other important existing platforms

Apart from Piclo, there are other important local platforms for system services, such as GOPACS in the Netherlands or NODES in Norway. These platforms are therefore briefly described below.

2.4.2.1 GOPACS (Netherlands)

GOPACS (Grid Operator Platform for Congestion Solutions) is a project developed by Dutch grid operators in order to manage congestion in the power grid. Similar to Piclo, GOPACS allows grid operators and service providers flexibility negotiations and service agreements to manage system congestion and ensure system stability [30].

With a collaborative approach, GOPACS is another interface through which multiple network operators collaborate to effectively identify and resolve different congestion problems. Again, the platform employs an auction mechanism to manage the contracting of flexibility services and ensure transparency in price formation. However, unlike Piclo, the GOPACS offering does not provide as many flexibility services but focuses mostly on congestion management [30].

2.4.2.2 NODES (Norway)

NODES is an active flexibility market solution with higher presence in Nordic region through which different electricity market players can buy and sell flexibility services in real time. Designed with the aim of facilitating the integration of renewables and DERs, NODES stands out from the rest by its operation at different points in the grid ranging from distribution to transmission, as well as by focusing on both transparency and efficiency [31]

Among the most outstanding features of NODES is the use of state-of-the-art technology, thus ensuring market operation optimization. The software implements intelligent algorithms to coordinate the supply and demand of flexibility services so that they are offered in an efficient and competitive manner. Furthermore, the active participation of both consumers and prosumers is possible with NODES, giving them the possibility to participate and contribute with their generation capacity and demand responsiveness. Figure 9 shows an image of this platform [31]

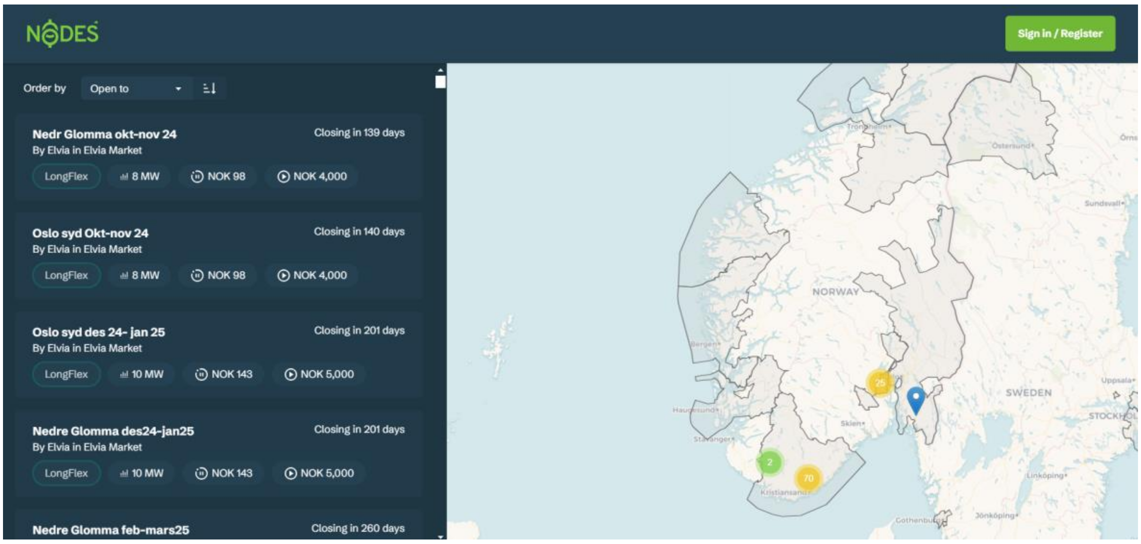

Figure 9: NODES platform [32]

2.5 Detailed description of the products studied

In this context of local system services markets, different types of products exist in order to meet the different operational needs of the electricity system. The products that have been studied and analyzed in this work are explained and described below, taking into account that these products can be remunerated both for their availability and their use, depending on the type of product in question and the conditions determined by the distribution system operator (DSO):

- **Secure**: This product is designed to manage operational limits in periods where demand or generation is high. Distributed energy resources are compensated for being available for a set time and for activation at peak periods. They are activated to assist with load management and to prevent the grid from becoming saturated. Notification of usage requirements varies from one week to one day before the time-of-use. Table 1 shows the features of this product [33].

Table 1: Secure product features [33]

Use Case	Availability £/MW/h	Utilisation £/MWh
Pre-fault	Yes, Payment	Yes, Payment
This product aims to resolve operational constraints (peak shaving)		

- **Sustain**: This service is used to manage peak demand as well as to relieve network load during scheduled events. The likelihood of needing the flexibility provided is quite high. Service windows are agreed in advance and are fixed for the duration of the contract. This service is remunerated only for usage, not for availability. Table 2 shows the features of this product [33].

Table 2: Sustain product features [33]

Use Case	Availability £/MW/h	Utilisation £/MWh
Scheduled	No	Yes, Payment
This product aims to address scheduled forecast overload		

- **Dynamic**: This product guarantees the continuous supply of energy despite unexpected events and different anomalies that may occur in the network. The reaction of DERs in these cases must be immediate, since they are contracted for the purpose of providing real-time services. This product is remunerated on a usage basis, although depending on the DSO, it can also be remunerated on an availability basis. Due to the unpredictable nature of failures and the urgency of the required response, the utilisation rate is generally higher. Table 3 shows the features of this product [33].

Table 3: Dynamic product features [33]

Use Case	Availability £/MW/h	Utilisation £/MWh
Post-fault	It depends on DSO	Yes, Payment
This product aims in network abnormality or in planned outage		

- **Restore**: This service is used to assist in system restoration, especially when major equipment failures occur. Due to the uncertainty in the demand for this service, the Restore product operates as a premium "utilisation-only" service. Thus, any response that helps to normalize the network will be remunerated, but there will be no payment for availability. Table 4 shows the features of this product [33].

Table 4: Restore product features [33]

Use Case	Availability £/MW/h	Utilisation £/MWh
Post-fault grid restoration	No	Yes, Payment
This product aims to restore the network		

These products enable DERs to provide flexibility to the power system so that the grid can support and tolerate variations in generation and demand in an efficient and effective manner. A more detailed summary of the characteristics of these products is shown in Figure 10.

Service parameters	SUSTAIN	SECURE	DYNAMIC	RESTORE
Minimum declarable capacity	50kW	50kW	50kW	50kW
Minimum utilisation	30 mins	30 mins	30 mins	30 mins
Utilisation notification period	Scheduled in advance	1 week in advance	Real time	Real time
Maximum ramping period	N/A	<15 mins	<2 mins	<2 mins
Availability agreement period	N/A	Contract stage	Contract stage	Contract stage
When required?	Scheduled forecast overload	Pre-fault / peak shaving	Network abnormality / planned outage	Network abnormality
Risk to network	Low	Medium	High	High
Utilisation certainty	High	High	Low	Low
Frequency of use	High	Medium	Low	Low

Figure 10: Characteristics of the different flexibility products [34]

3. Methodology

The methodology followed in this work consists of two fundamental parts. The first consists of an analysis of market competitiveness, for which the HHI index is used, and the second consists of the construction of regression models and correlation matrices in order to analyze the possible relationships that different variables may have on the price of products, thus fulfilling the objectives of this work.

3.1. Market competitiveness study – HHI index

Market competitiveness analysis is a fundamental procedure for examining and understanding the market structure and the distribution of power among the different market participants or suppliers. One of the main methods to examine this market concentration is through the Herfindahl-Hirschman Index (HHI). This index gives a quantitative value of the competitiveness in the market, so that it can be used to determine whether the market is dominated by only a few players or whether, on the contrary, it is composed of a large number of players of comparable size.

The HHI is calculated by taking the sum of the squares of the market shares of each supplier in the market. The mathematical formula is as follows:

$$HHI = \sum_{i=1}^{N} (s_i * 100)^2$$

where s_i is the market share of supplier i and N is the number of suppliers in the market. The market share is expressed as a decimal, and multiplied by 100 to convert it into a percentage.

The HHI value is a number that can range from almost 0 to 10,000. An HHI value of 10,000 would imply a monopoly, where only one company is present in the market, while an HHI value close to 0 would reflect a very competitive market, with a large number of suppliers of almost the same size. According to the U.S. Department of Justice and Federal Trade Commission guidelines [35]

- An HHI below 1,500 reflects an unconcentrated market.
- An HHI in the range of 1,500 to 2,500 suggests a moderately concentrated market.
- An HHI greater than 2,500 is indicative of a highly concentrated market.

The HHI is used in this paper to examine and evaluate the degree of competitiveness in the system's local service markets. This analysis is performed both in general, by product type and by geographic area.

First, the HHI is calculated as a single figure showing the overall market concentration, so that it is possible to deduce whether the market is highly concentrated with only a few large providers or whether the market is more dispersed with a multitude of small bidders.

Next, the same procedure is followed to calculate this time the HHI index for each of the products studied (Secure, Sustain, Dynamic and Restore), so that it is possible to determine whether there is greater concentration in some product options than in others, thus reflecting the differences present in the competitiveness between the different types of flexibility products.

Finally, a disaggregated analysis is also performed by calculating the HHI index in each of the locations contained in the data. This approach will make it possible to analyze the market concentration of each geographic region in isolation, a very useful tool for the design of differentiated policies that facilitate the promotion of competition at the local level.

Ultimately, the HHI breakdown provides greater clarity on market structure and competition in the system's local service markets.

3.2. Analysis and prediction models

This section explains the procedure used in this work to identify the most influential factors in the determination of product prices. To this end, correlation matrices are used to get a general idea of which variables have the greatest impact on price, and regression models are used to quantify the real effect of the variables on the price of the products and thus draw conclusions about the market.

3.2.1 Correlation matrix

The correlation matrix is a statistical technique that provides insight into the relationship that exists between two or more variables. In the study carried out in this work, the correlation matrix is used to establish the correlations existing between the dependent variable, the price of flexibility products (both availability and utilisation price), and the explanatory variables, as is the case of connection voltage (kV), provider, technology, location, number of bids received, flexible capacity (MW) and maximum run time (hh:mm). These variables are used because they are those that present variations in the data that, in this way, can reflect the differences in the prices of the products, as well as because it is thought that they can be relevant in the study. A more detailed description of these variables is presented in the results section.

The Pearson correlation coefficient is a number between -1 and 1 showing the strength with which the two variables are related. A correlation coefficient of 1 shows a perfect positive correlation, a value of -1 shows a perfect negative correlation, and a value of 0 shows that there is no correlation between the variables. The correlation matrix provides an overview of all the correlations between the different variables in the same table, thus facilitating the identification of different patterns and interesting relationships.

This paper first obtains the correlation matrix for all the variables involved in the study, and then analyze the correlations between price and the rest of the variables analyzed, which indicates in advance how the different variables may or may not be correlated with the prices of the products studied. The identification of important correlations can guide the construction and development of the regression models by providing a general idea of which variables may have a higher probability of influencing the determination of product prices.

3.2.2 Regression models

Once the possible relationships between price and the different variables are identified through the correlation matrix, regression models are developed to evaluate the effect and impact of these variables on the price of flexibility products. Regression models are mathematical models that quantify the level at which a dependent variable (the variable of interest, in this case, price) changes as a function of one or more independent variables.

For this study, multivariate linear regression models are used. These models are useful when the impact of a set of independent variables on a continuous dependent variable is to be examined. The general formula for a multiple linear regression model is as follows:

$$Y = \beta_0 + \beta_1 * X_1 + \beta_2 * X_2 + \ldots + \beta_n * X_n + \epsilon$$

where:

- Y is the dependent variable (in this case, the price of the flexibility product).
- β_0 is the constant or the ordinate to the origin (intercept).
- β_1, β_2, …, β_n are the regression coefficients reflecting the change in Y per one unit change in the variables X_1, X_2, …, X_n, respectively.
- ϵ is the error term.

For each type of product, regression models are estimated for both the availability price and the utilisation price, provided that the prices of the products are not zero.

The process begins with creating a general model for each type of product, evaluating the significance of each variable and its impact on price. The significance of the variables in the regression models is evaluated by the p-value. A low p-value, less than 0.05, indicates that the independent variable has a significant effect on the dependent variable. Otherwise, if the p-value is greater than 0.05, the result of the statistical test is not considered to be statistically significant.

Subsequently, specific models are developed for each location, allowing to identify the variables that have a greater impact on price in different areas, and also allowing to identify those variables that are not significant.

The results of the regression models provide a detailed understanding of the factors that influence the price of flexibility products in local markets, information that will be critical for identifying trends and patterns.

4. Analysis of results

4.1 Market competitiveness analysis

This section presents the analysis of market competitiveness based on the Herfindahl-Hirschman Index (HHI). As explained above, the HHI is a measure of market concentration and is calculated by adding the squares of the market shares of all suppliers. A high HHI value indicates higher concentration and, therefore, lower competitiveness.

First, a generic analysis of the HHI index has been performed considering all the offers accepted in the market in the available data, without distinguishing by product type or location. The HHI index value obtained for this case is 7237.84. This result indicates a highly concentrated market, which implies that a few large providers dominate the supply of services in the system. In this case, one supplier stands out from the rest: of the 3652 accepted bids, 3099 were from the supplier Octopus Energy, which explains this very high HHI index value. Among the other suppliers, Gridimp Ltd. stood out with 128 accepted bids, and Ohme Operations UK Ltd with 124.

To obtain a more detailed understanding of the competitiveness of the market, the analysis was then broken down by product type, with the results shown in Table 5:

Table 5: HHI index by product

	Secure	Sustain	Dynamic	Restore
HHI Index	2342.90	8490.91	3155.56	3491.12
Accepted bids	389	3235	15	13

It can be seen how, firstly, the HHI index for the Sustain product is very high, almost 8500, which indicates a very high concentration of the market, since, of the 3099 accepted offers of Octopus Energy, 2978 are for this product.

The Dynamic and Restore products have indices of the same order, also suggesting a high concentration in these products, although not as extreme as in the case of Sustain. In both cases, the number of accepted bids is quite low, so there are also few suppliers of these products.

The Secure product is the only one with a value below 2500, suggesting a moderate market concentration, indicating that, although there are some large suppliers, the market is relatively competitive.

Finally, to assess the competitiveness of the market at the local level, the HHI index has been calculated for each of the locations available in the data. A histogram showing the distribution of the HHI values by intervals is presented in Figure 11, with the number of locations in each interval represented on the y-axis:

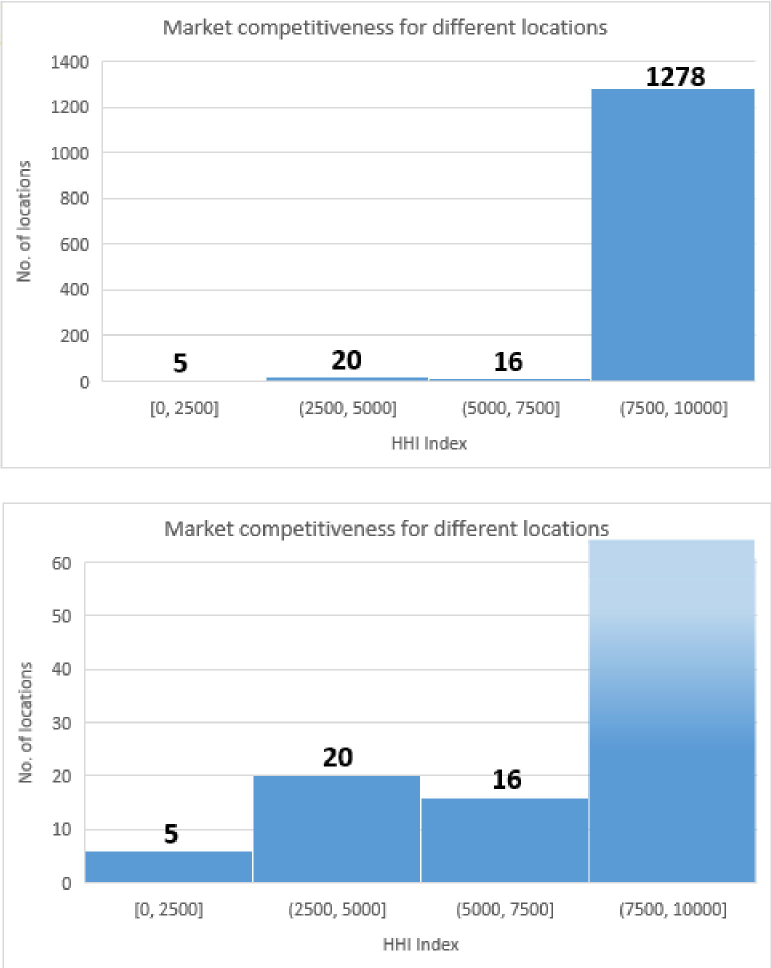

Figure 11: Market competitiveness for different locations

The histogram reveals that the market is competitive in only 5 locations: Carrington - Fiddlers Ferry, Cellarhead, Kaimes, Lister Drive and Trawsfynydd. Furthermore, in 36 locations it is highly concentrated, and 1278 locations have an HHI index of 10000, which is an absolute monopoly, i.e. a single supplier controls the entire market in all these locations. In such cases, competition is non-existent and the dominant provider may have total control over prices and service offerings, which can lead to market inefficiencies, higher prices and less innovation.

4.2 Secure product

4.2.1 Availability Price

First, the variation and dispersion in the availability prices of the Secure product are analyzed, for which two types of graphs have been generated: a histogram (Figure 12) and a boxplot (Figure 13).

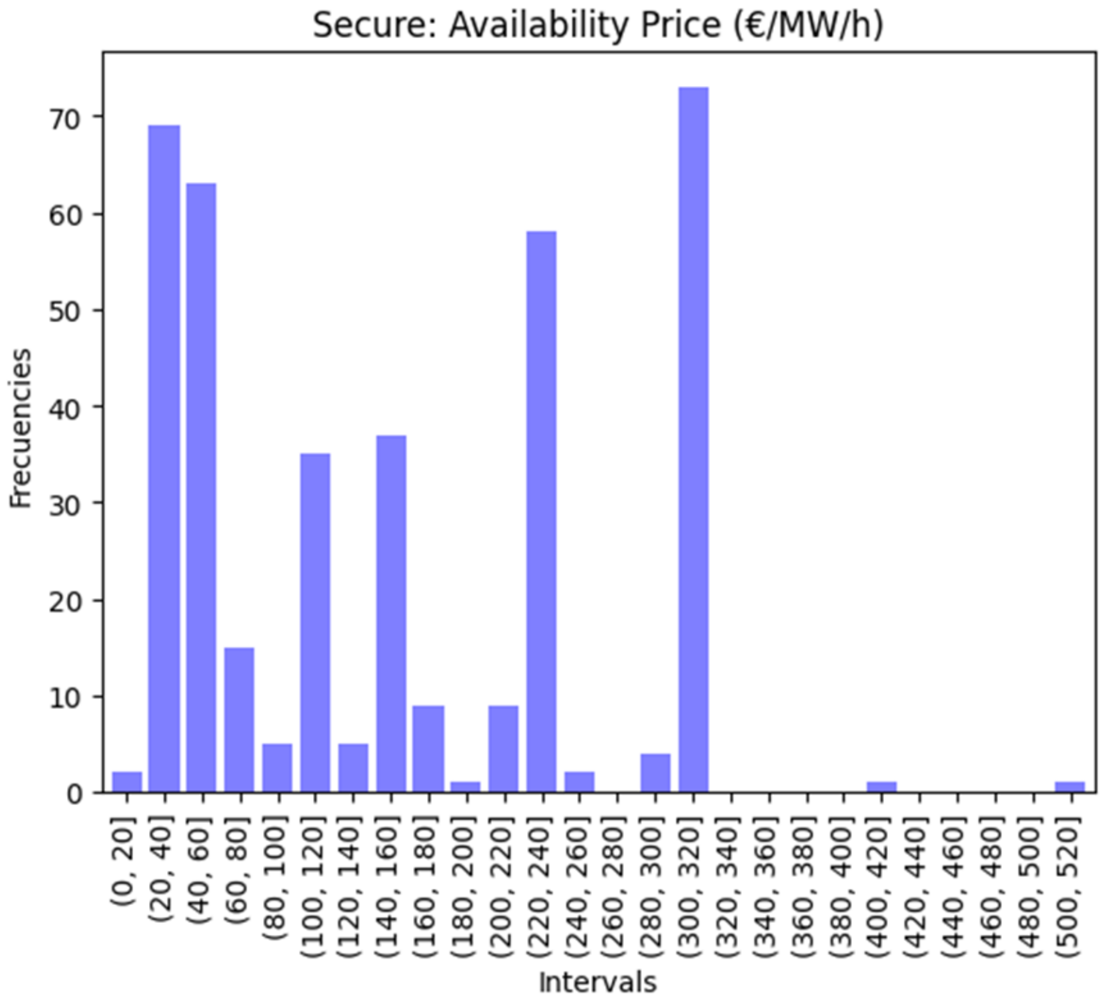

Figure 12: Histogram of Secure's availability prices

Figure 12 shows how the availability prices for the Secure product are distributed, with prices widely spread up to 320 €/MW/h, and with prices also reaching 500 €/MW/h in some cases. This dispersion suggests a large variability in the prices offered and accepted in the market.

Figure 13: Boxplot of Secure's availability prices

Figure 13 provides a more detailed view of the variation of availability prices in line with the above. In addition, the average availability price for this product, which is 156.59 €/MW/h, is also represented.

In order to explain the variability and dispersion of prices and analyze the factors that may affect them, a multivariate regression model has been carried out in which the following variables have been included in the model:

- **Service provider**: Name/identifier of the flexibility service provider.
- **Main technology**: Main technology used against each tender reference (fossil – gas, demand, stored energy, water).
- **Service location (Grid supply point)**: The area within which a flexibility service is being procured.
- **Connection voltage (in kV)**: Voltage at which a connection is made.
- **Number of bids received**: Number of bids received for each tender reference.
- **Flexible capacity (in MW)**: For firm contracts, this is a committed level of generation or consumption adjustment that can be delivered on request relative to their baseline generation or consumption level. For non-firm contracts, this is the maximum amount that the generation or consumption can be adjusted relative to an assumed baseline generation or consumption level.
- **Maximum run time (hh:mm)**: The maximum time in minutes for which the solution can continuously deliver its flexible capacity.

But before doing so, first of all, the correlation matrix was used to obtain the correlations between the availability price and the different variables, in order to get an initial idea of the variables that could have the greatest influence on price differences, as shown in Figure 14.

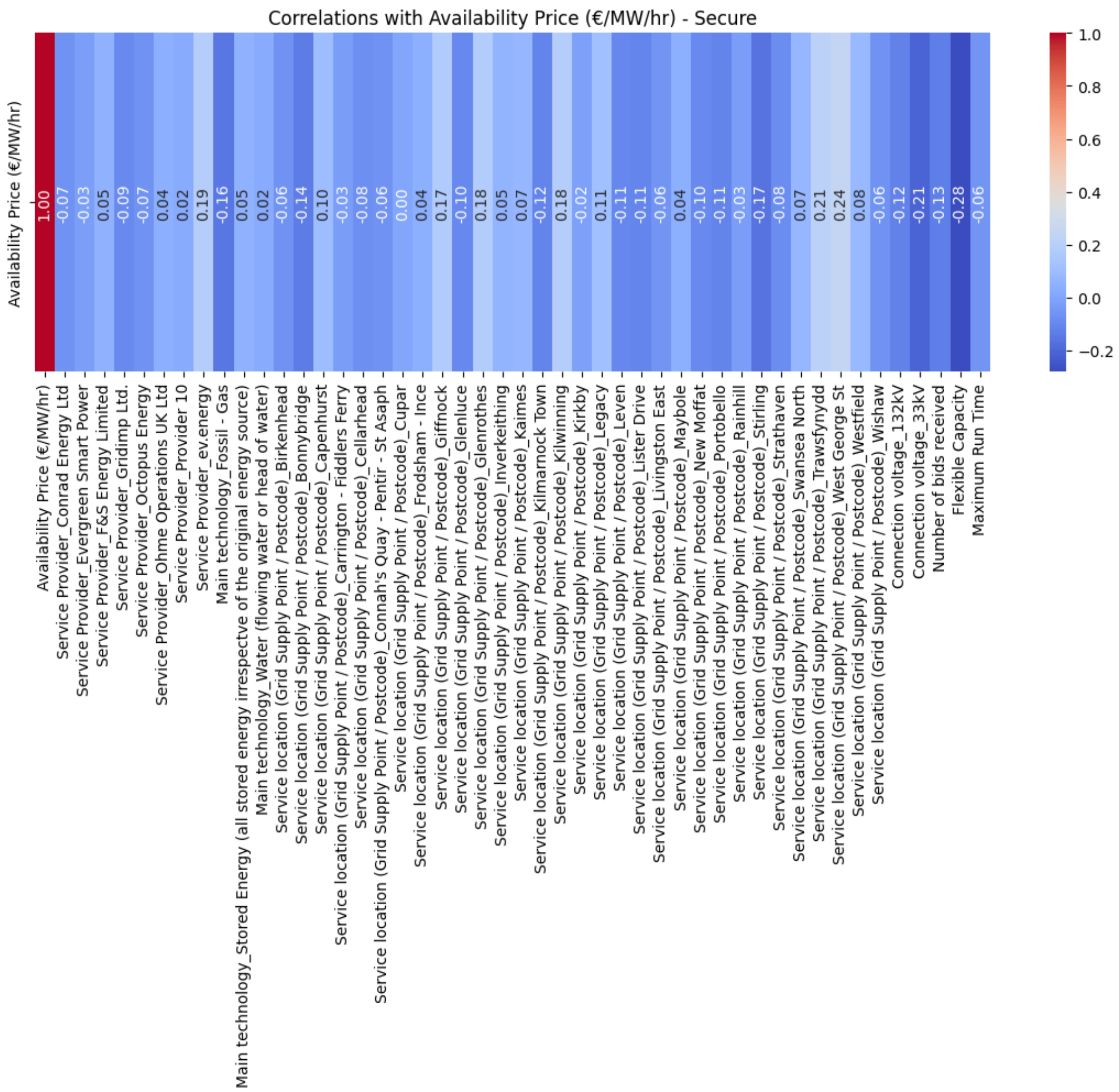

Figure 14: Correlations with availability price for Secure product

The results of the correlation matrix indicate that some variables show stronger correlations with availability price, such as voltage, grid supply point location or flexible capacity. These correlations suggest that these variables could have a notable impact on the variability of availability prices.

This initial analysis of correlations provides a basis for developing regression models that quantify the specific impact of these variables on availability prices. Next, the availability price regression model for the Secure product is presented, which allow for a deeper understanding of the factors influencing price formation in the system's local utility markets. The same variables as in the correlation matrix are included in this model, and the results are shown in Table 6 and Table 7.

Model Results for Availability Price (€/MW/hr) – Secure

Table 6: Overall results of Secure's availability price model

Description	Value
Dependent Variable	Availability Price (€/MW/hr)
Model	OLS
Method	Least Squares
R-squared	0.534
Adjusted R-squared	0.475
F-statistic	8.965
Prob (F-statistic)	1.16e-35

Table 7: Coefficients of Secure's availability price model

Variable	coef	std err	t	P>|t|
const	117.4259	24.85	4.725	0.0
Service Provider_Conrad Energy Ltd	-423.4291	394.084	-1.074	0.283
Service Provider_Evergreen Smart Power	-97.1126	135.346	-0.718	0.474
Service Provider_F&S Energy Limited	-52.6359	76.124	-0.691	0.49
Service Provider_Gridimp Ltd.	-116.3678	124.55	-0.934	0.351
Service Provider_Octopus Energy	-55.1404	51.914	-1.062	0.289
Service Provider_Ohme Operations UK Ltd	117.6376	121.323	0.97	0.333
Service Provider_Provider 10	-18.7775	69.772	-0.269	0.788
Service Provider_ev.energy	9.4288	76.164	0.124	0.902
Main technology_Fossil - Gas	330.3936	412.468	0.801	0.424
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	-52.6359	76.124	-0.691	0.49

Main technology_Water (flowing water or head of water)	-18.7775	69.772	-0.269	0.788
Service location (Grid Supply Point / Postcode)_Birkenhead	84.3335	40.663	2.074	0.039
Service location (Grid Supply Point / Postcode)_Bonnybridge	-66.3613	39.758	-1.669	0.096
Service location (Grid Supply Point / Postcode)_Capenhurst	159.7159	45.89	3.48	0.001
Service location (Grid Supply Point / Postcode)_Carrington - Fiddlers Ferry	53.8589	28.324	1.901	0.058
Service location (Grid Supply Point / Postcode)_Cellarhead	14.1355	28.896	0.489	0.625
Service location (Grid Supply Point / Postcode)_Connah's Quay - Pentir - St Asaph	29.1223	35.437	0.822	0.412
Service location (Grid Supply Point / Postcode)_Cupar	10.6384	34.512	0.308	0.758
Service location (Grid Supply Point / Postcode)_Frodsham - Ince	146.7056	81.884	1.792	0.074
Service location (Grid Supply Point / Postcode)_Giffnock	133.5563	37.787	3.534	0.0
Service location (Grid Supply Point / Postcode)_Glenluce	-57.967	46.843	-1.237	0.217
Service location (Grid Supply Point / Postcode)_Glenrothes	182.3628	36.685	4.971	0.0
Service location (Grid Supply Point / Postcode)_Inverkeithing	69.8188	33.037	2.113	0.035
Service location (Grid Supply Point / Postcode)_Kaimes	94.934	34.028	2.79	0.006
Service location (Grid Supply Point / Postcode)_Kilmarnock Town	-65.813	45.87	-1.435	0.152

Service location (Grid Supply Point / Postcode)_Kilwinning	170.7581	34.41	4.962	0.0
Service location (Grid Supply Point / Postcode)_Kirkby	99.832	36.724	2.718	0.007
Service location (Grid Supply Point / Postcode)_Legacy	116.8416	28.126	4.154	0.0
Service location (Grid Supply Point / Postcode)_Leven	-12.5131	32.149	-0.389	0.697
Service location (Grid Supply Point / Postcode)_Lister Drive	4.1014	61.325	0.067	0.947
Service location (Grid Supply Point / Postcode)_Livingston East	-38.9677	61.007	-0.639	0.523
Service location (Grid Supply Point / Postcode)_Maybole	146.1303	81.883	1.785	0.075
Service location (Grid Supply Point / Postcode)_New Moffat	42.6779	54.944	0.777	0.438
Service location (Grid Supply Point / Postcode)_Portobello	28.0806	26.96	1.042	0.298
Service location (Grid Supply Point / Postcode)_Rainhill	6.6244	46.31	0.143	0.886
Service location (Grid Supply Point / Postcode)_Stirling	-57.5737	36.695	-1.569	0.118
Service location (Grid Supply Point / Postcode)_Strathaven	-1.2622	33.496	-0.038	0.97
Service location (Grid Supply Point / Postcode)_Swansea North	148.6427	33.868	4.389	0.0
Service location (Grid Supply Point / Postcode)_Trawsfynydd	180.0977	32.616	5.522	0.0
Service location (Grid Supply Point / Postcode)_West George St	211.204	34.476	6.126	0.0

Service location (Grid Supply Point / Postcode)_Westfield	170.4854	60.201	2.832	0.005
Service location (Grid Supply Point / Postcode)_Wishaw	-80.8725	82.268	-0.983	0.326
Connection voltage_132kV	-45.5439	58.272	-0.782	0.435
Connection voltage_33kV	-100.8633	17.019	-5.926	0.0
Number of bids received	10.3571	8.207	1.262	0.208
Flexible Capacity	-10.5766	5.832	-1.814	0.071
Maximum Run Time	-96.2927	115.605	-0.833	0.405

It can be seen how, of all the variables included in the model, only the voltage (in the case of 33 kV) and some locations (42%, specifically) are significant, these having the highest coefficients and, therefore, the greatest impact on price.

Thus, a multivariate regression model is now performed for each of the locations, in order to analyze the reason why the different locations present such price differences. Again, the same variables are used as before, except for the location, obviously, since a model is built for each location. It should be noted that certain locations may not have data relating to a particular supplier, so that, for example, a supplier may not appear in the models. The same may occur with the rest of the variables. The results of the different models are shown in Figure 15:

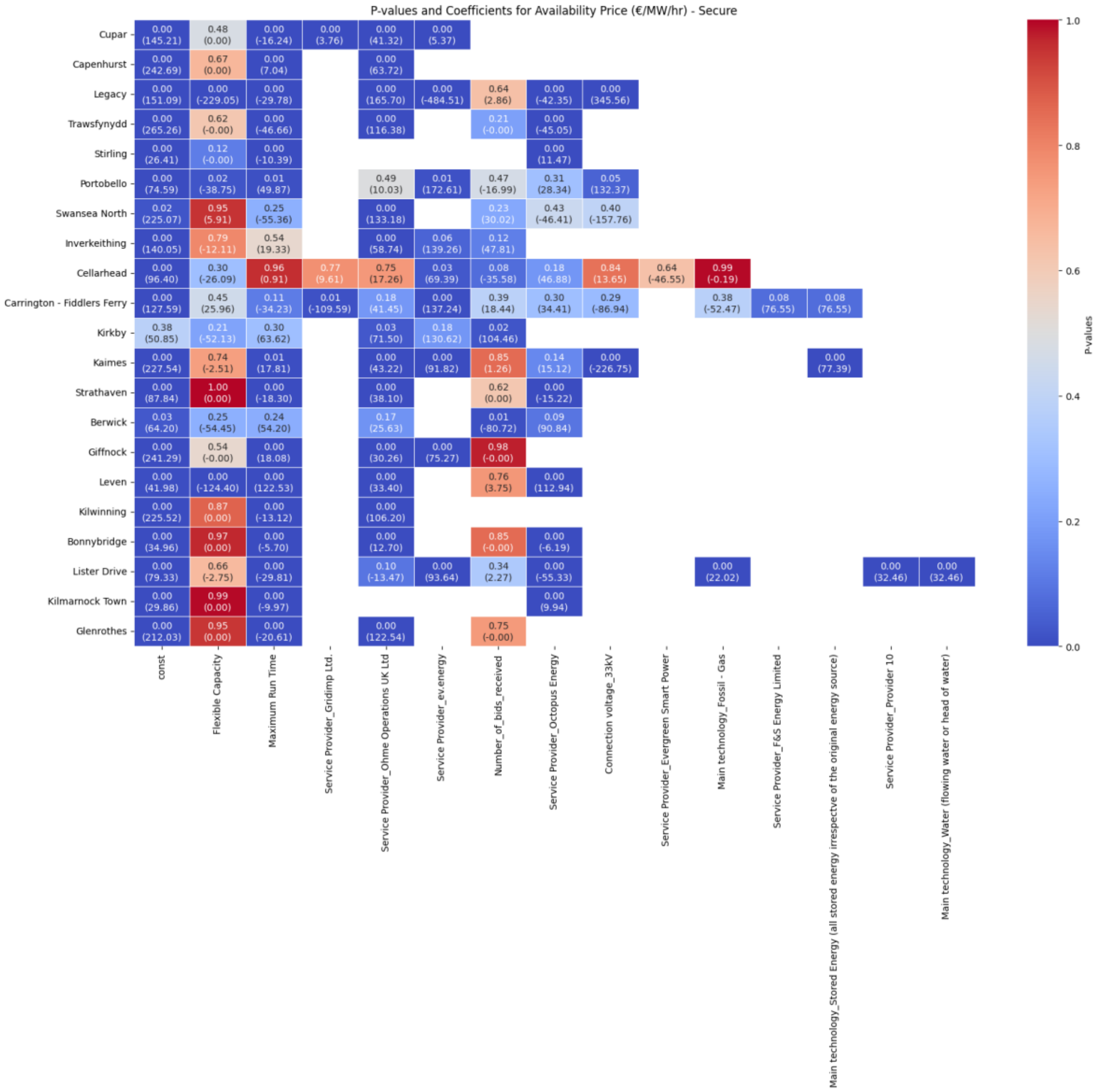

Figure 15: Location regression models for availability price for Secure product

As can be seen, in 16 of 21 locations, or 76% of the locations, the significant variable with the greatest impact on price was the provider, suggesting that the identity of the provider is a crucial factor in determining availability prices. In the remaining locations, the number of bids received was the variable with the greatest impact on price in 2 locations, and the voltage, the flexible capacity, and the maximum run time were significant in only one location. The type of technology was not significant in any case.

It should be noted that there are certain locations where the regression model could not be calculated because there was insufficient data or because of the lack of variation in the data. For these cases, the average price of availability in these locations is plotted in Figure 16 against the overall average price of availability of the Secure product, showing locations with the price significantly higher (such as West George St or Westfield) and lower (such as Wishaw, New Moffat or Glenluce) than the average price:

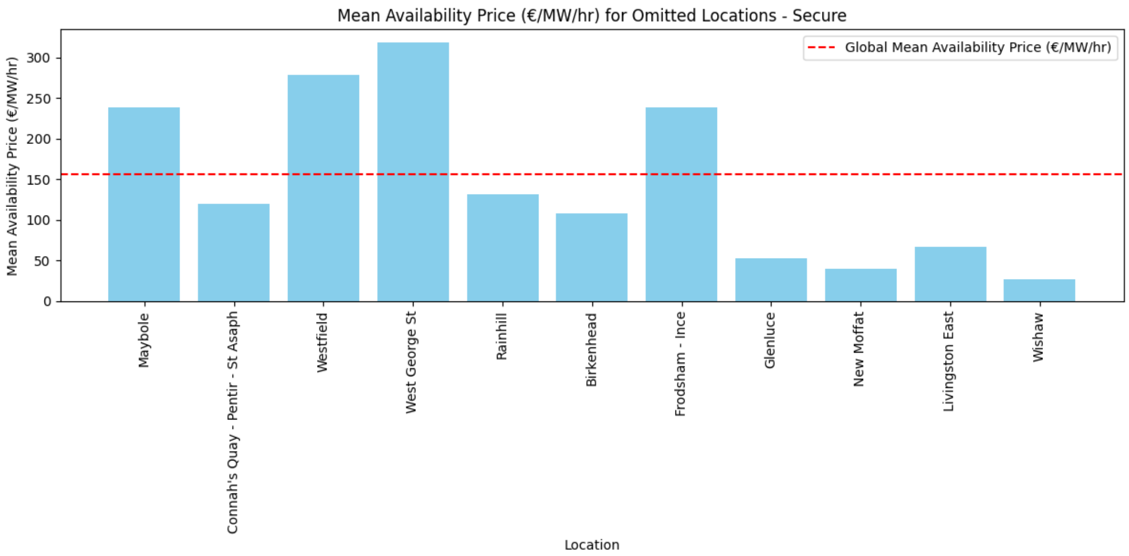

Figure 16: Mean availability price for omitted locations for Secure product

4.2.2 Utilisation Price

Now the variation and dispersion in the utilisation prices of the Secure product is analyzed:

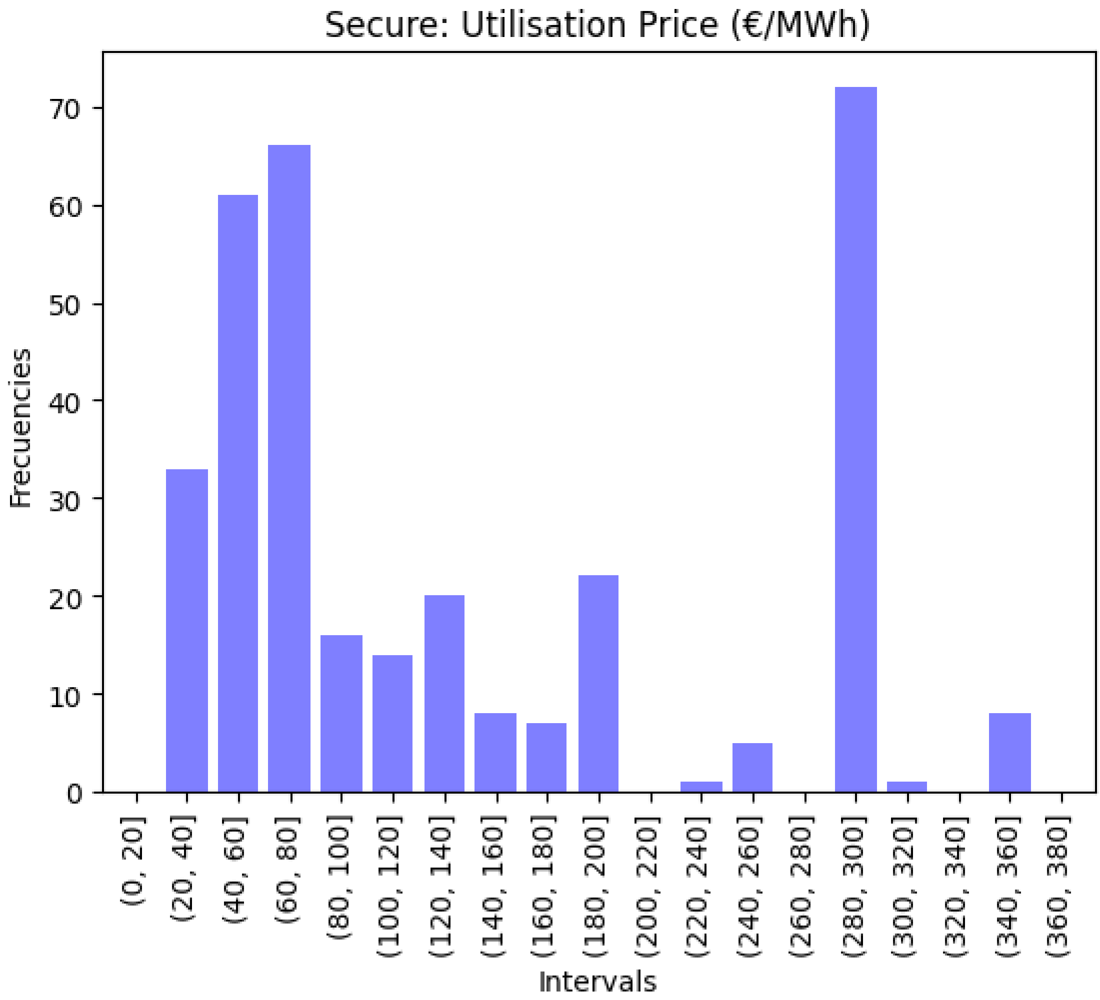

Figure 17: Histogram of Secure's utilisation prices

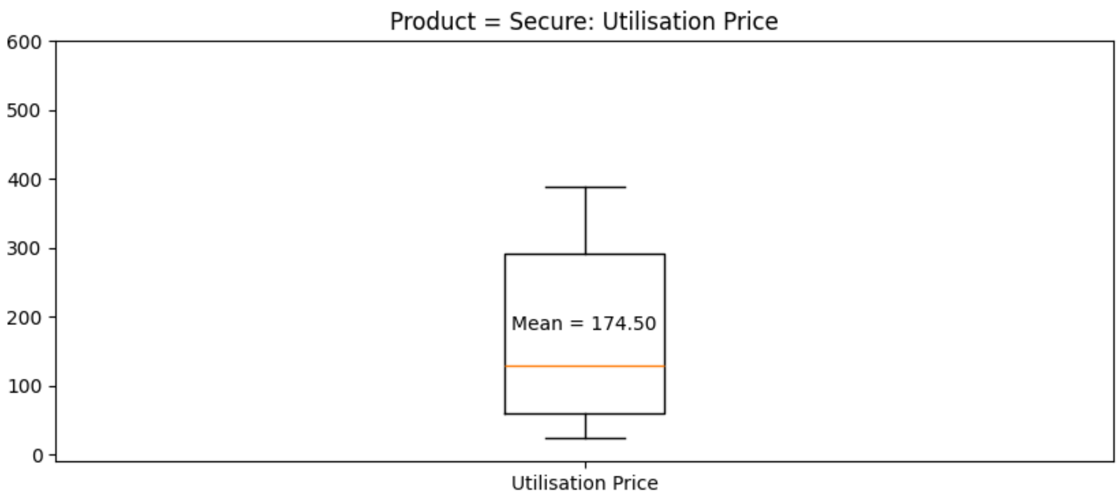

Figure 18: Boxplot of Secure's utilisation prices

The histogram (Figure 17) shows how the utilisation prices for the Secure product are distributed, with prices widely distributed up to 300 €/MWh, a dispersion that suggests a great variability in the prices offered and accepted in the market.

The boxplot (Figure 18), on the other hand, provides a more detailed view of the variation in utilisation prices in line with the above. In addition, the average utilisation price for this product, which is 174.50 €/MWh, is also plotted.

As previously done, to explain the variability and dispersion of prices and to analyze the factors that may affect them, a multivariate regression model has been carried out in which the same variables as in the previous case have been included.

The correlation matrix was used to obtain the correlations between the utilisation price and the different variables, in order to get an initial idea of the variables that could have the greatest influence on price differences, as shown in Figure 19.

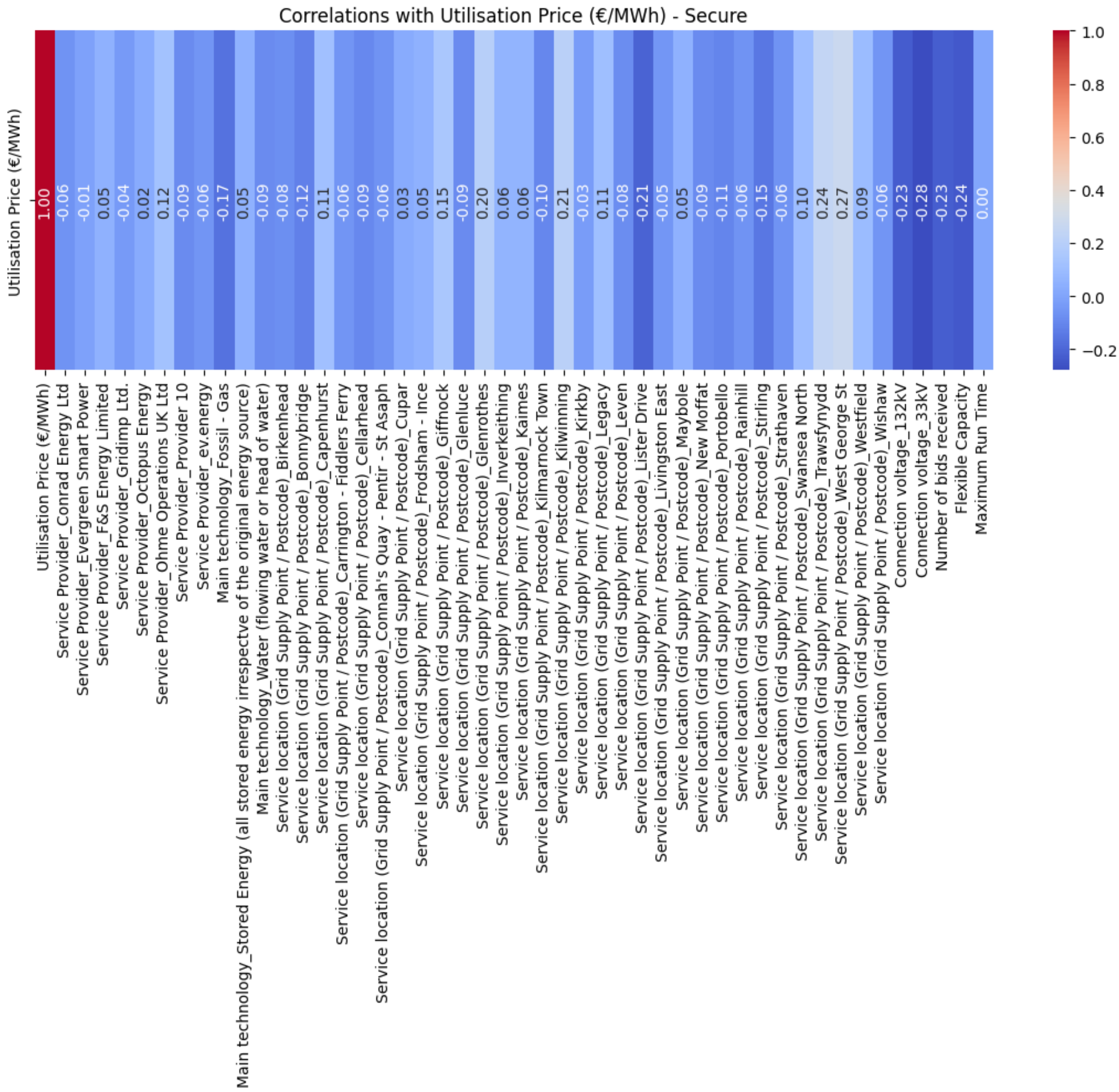

Figure 19: Correlations with utilisation price for Secure product

The results of the correlation matrix indicate that some variables show stronger correlations with the utilisation price, such as the voltage, the location of the network supply point, the flexible capacity or the number of bids received. These correlations suggest that these variables could have a notable impact on the variability of utilisation prices.

This initial analysis of the correlations provides a basis for developing regression models that quantify the specific impact of these variables on utilisation prices. The utilisation price regression model for the secure product is presented below, which will allow a deeper understanding of the factors influencing price formation in the local service markets of the system. Table 8 and Table 9 show the results of this model.

Model Results for Utilisation Price (€/MWh) – Secure

Table 8: Overall results of Secure's utilisation price model

Description	Value
Dependent Variable	Utilisation Price (€/MWh)
Model	OLS
Method	Least Squares
R-squared	0.562
Adjusted R-squared	0.506
F-statistic	10.04
Prob (F-statistic)	7.44e-40

Table 9: Coefficients of Secure's utilisation price model

Variable	coef	std err	t	P>|t|
const	115.7626	28.885	4.008	0.0
Service Provider_Conrad Energy Ltd	-173.7718	458.076	-0.379	0.705
Service Provider_Evergreen Smart Power	-1.8505	157.324	-0.012	0.991
Service Provider_F&S Energy Limited	5.8047	88.485	0.066	0.948
Service Provider_Gridimp Ltd.	-16.2571	144.775	-0.112	0.911
Service Provider_Octopus Energy	-3.6183	60.344	-0.06	0.952
Service Provider_Ohme Operations UK Ltd	57.5975	141.024	0.408	0.683

Service Provider_Provider 10	-3.3373	81.102	-0.041	0.967
Service Provider_ev.energy	6.8083	88.531	0.077	0.939
Main technology_Fossil - Gas	70.6154	479.446	0.147	0.883
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	5.8047	88.485	0.066	0.948
Main technology_Water (flowing water or head of water)	-3.3373	81.102	-0.041	0.967
Service location (Grid Supply Point / Postcode)_Birkenhead	121.8507	47.265	2.578	0.01
Service location (Grid Supply Point / Postcode)_Bonnybridge	-81.9781	46.214	-1.774	0.077
Service location (Grid Supply Point / Postcode)_Capenhurst	192.0832	53.341	3.601	0.0
Service location (Grid Supply Point / Postcode)_Carrington - Fiddlers Ferry	56.7389	32.924	1.723	0.086
Service location (Grid Supply Point / Postcode)_Cellarhead	33.5903	33.588	1.0	0.318
Service location (Grid Supply Point / Postcode)_Connah's Quay - Pentir - St Asaph	30.9249	41.191	0.751	0.453
Service location (Grid Supply Point / Postcode)_Cupar	47.2899	40.116	1.179	0.239
Service location (Grid Supply Point / Postcode)_Frodsham - Ince	175.2065	95.18	1.841	0.067
Service location (Grid Supply Point / Postcode)_Giffnock	170.9983	43.923	3.893	0.0
Service location (Grid Supply Point / Postcode)_Glenluce	-76.3643	54.449	-1.402	0.162

Service location (Grid Supply Point / Postcode)_Glenrothes	219.3152	42.642	5.143	0.0
Service location (Grid Supply Point / Postcode)_Inverkeithing	87.9121	38.401	2.289	0.023
Service location (Grid Supply Point / Postcode)_Kaimes	123.2598	39.553	3.116	0.002
Service location (Grid Supply Point / Postcode)_Kilmarnock Town	-79.3295	53.319	-1.488	0.138
Service location (Grid Supply Point / Postcode)_Kilwinning	207.7779	39.998	5.195	0.0
Service location (Grid Supply Point / Postcode)_Kirkby	158.6546	42.688	3.717	0.0
Service location (Grid Supply Point / Postcode)_Legacy	138.8461	32.693	4.247	0.0
Service location (Grid Supply Point / Postcode)_Leven	-13.6115	37.37	-0.364	0.716
Service location (Grid Supply Point / Postcode)_Lister Drive	14.971	71.284	0.21	0.834
Service location (Grid Supply Point / Postcode)_Livingston East	-56.7017	70.914	-0.8	0.425
Service location (Grid Supply Point / Postcode)_Maybole	174.861	95.18	1.837	0.067
Service location (Grid Supply Point / Postcode)_New Moffat	58.7422	63.866	0.92	0.358
Service location (Grid Supply Point / Postcode)_Portobello	27.9336	31.338	0.891	0.373
Service location (Grid Supply Point / Postcode)_Rainhill	-13.9435	53.83	-0.259	0.796
Service location (Grid Supply Point / Postcode)_Stirling	-74.9957	42.654	-1.758	0.08
Service location (Grid Supply Point / Postcode)_Strathaven	-3.7078	38.935	-0.095	0.924

Service location (Grid Supply Point / Postcode)_Swansea North	188.2433	39.368	4.782	0.0
Service location (Grid Supply Point / Postcode)_Trawsfynydd	219.6924	37.912	5.795	0.0
Service location (Grid Supply Point / Postcode)_West George St	256.8607	40.074	6.41	0.0
Service location (Grid Supply Point / Postcode)_Westfield	207.6142	69.977	2.967	0.003
Service location (Grid Supply Point / Postcode)_Wishaw	-106.6256	95.627	-1.115	0.266
Connection voltage_132kV	-94.8536	67.734	-1.4	0.162
Connection voltage_33kV	-143.4908	19.783	-7.253	0.0
Number of bids received	6.3972	9.539	0.671	0.503
Flexible Capacity	-6.3514	6.779	-0.937	0.349
Maximum Run Time	-20.0033	134.378	-0.149	0.882

From all the variables included in the model, once again, only the voltage (in the case of 33 kV) and the same locations as for the availability price (42% also) are significant, these having the highest coefficients and, therefore, the greatest impact on the price.

Thus, a multivariate regression model is now performed for each of the locations, to analyze the reason why the different locations show such price differences. The results of the different models are shown in Figure 20:

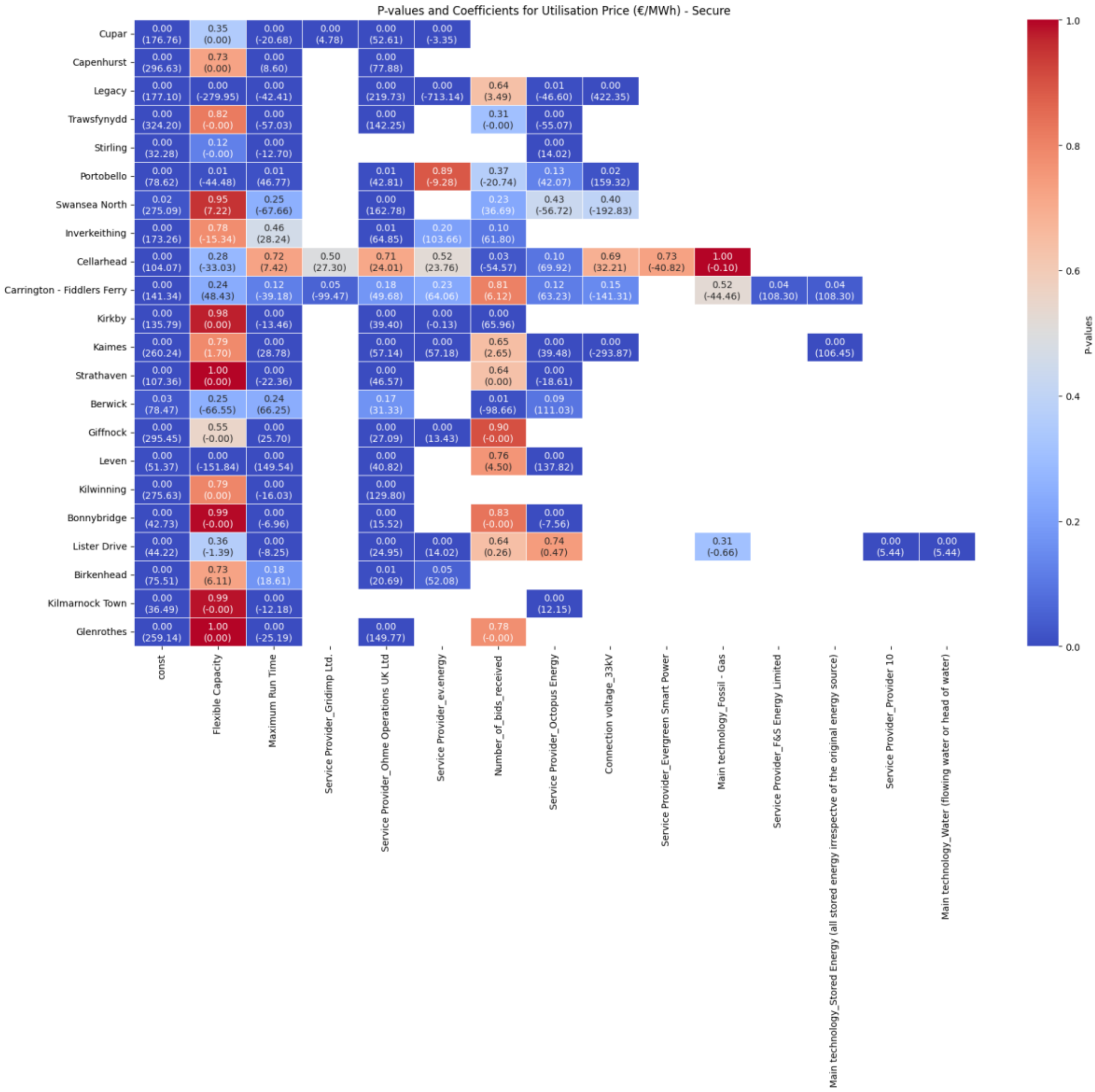

Figure 20: Location regression models for utilisation price for Secure product

In 14 of 22 locations, or 64% of the locations, the significant variable with the greatest impact on price was the provider, suggesting that the identity of the provider is also a crucial factor in determining utilisation prices. In the remaining locations, the number of bids received was the variable with the greatest impact on price in 3 locations, followed by voltage in 2, and the flexible capacity, the maximum run time and technology in only one.

As before, it should be noted that there are certain locations where the regression model could not be calculated because there was insufficient data to calculate it or because of the lack of variation in the data. For these cases, the average utilisation price at these locations is plotted in Figure 21 against the overall average utilisation price of the Secure product, showing locations with the price significantly higher (e.g. West George St or Westfield) and lower (e.g. Wishaw, New Moffat or Glenluce) than the average price, observing a similar price distribution to that of the availability price:

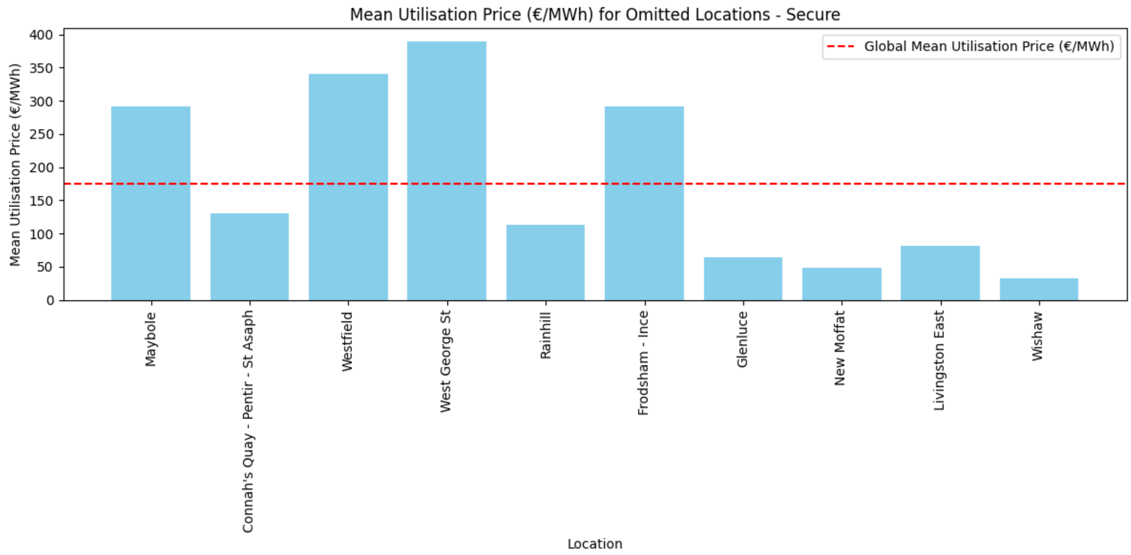

Figure 21: Mean utilisation price for omitted locations for Secure product

4.3 Sustain product

4.3.1 Utilisation price

The Sustain product, as explained in the state of the art, is only paid per use, so the analysis is simply carried out for this case. First, the variation and dispersion in the utilisation prices of the Sustain product is analyzed:

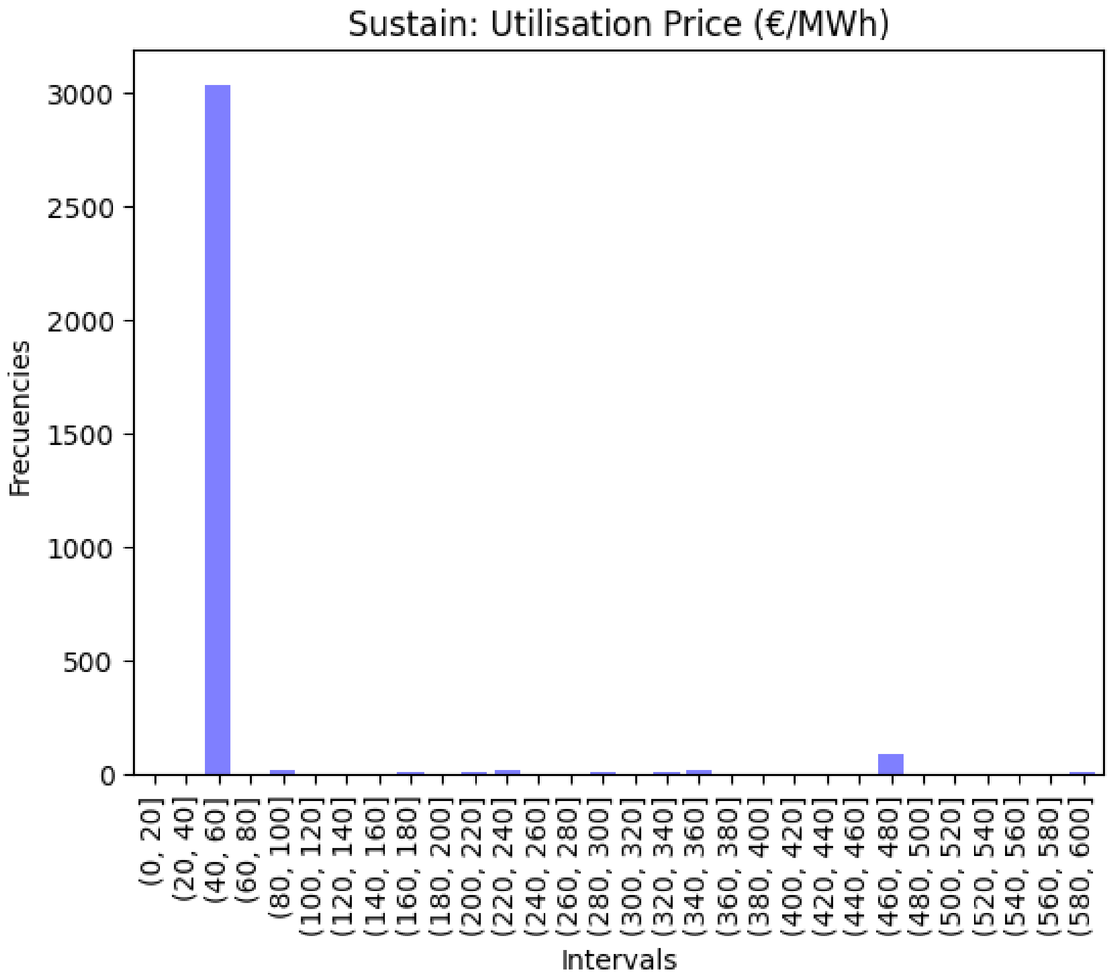

Figure 22: Histogram of Sustain's utilisation prices

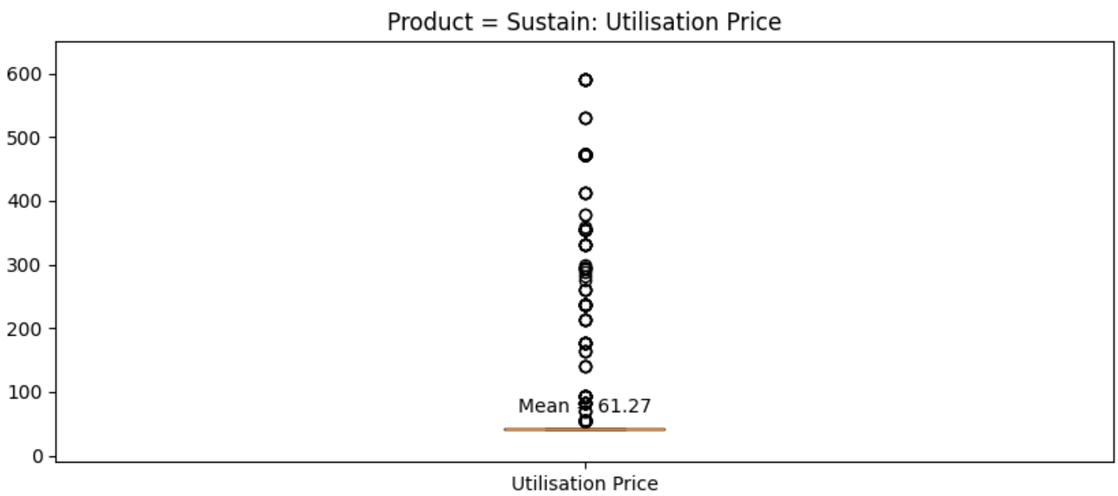

Figure 23: Boxplot of Sustain's utilisation prices

The histogram (Figure 22) shows how utilisation prices are distributed for the Sustain product, with prices mainly concentrated between 40 and 60 €/MWh, but with prices also reaching up to 600 €/MWh, so that price dispersion, although less than in the case of Secure, is also present in the case of Sustain.

The boxplot (Figure 23), on the other hand, provides a more detailed view of the variation in utilisation prices, with the presence of numerous outliers that raise the average price of this product to 61.27 €/MWh.

As in the case of the Secure product, in order to explain the variability and dispersion of prices and to analyze the factors that may affect them, a multivariate regression model has been run again, including the same variables as in the previous case. In this case, due to the high number of locations present, a first model has been run considering all of them, and those with a p-value close to 1, i.e. 1283 locations, have been discarded, so that the simplified model is analyzed and presented.

As a preliminary analysis, the correlations between the utilisation price and the different variables were obtained, as shown in Figure 24:

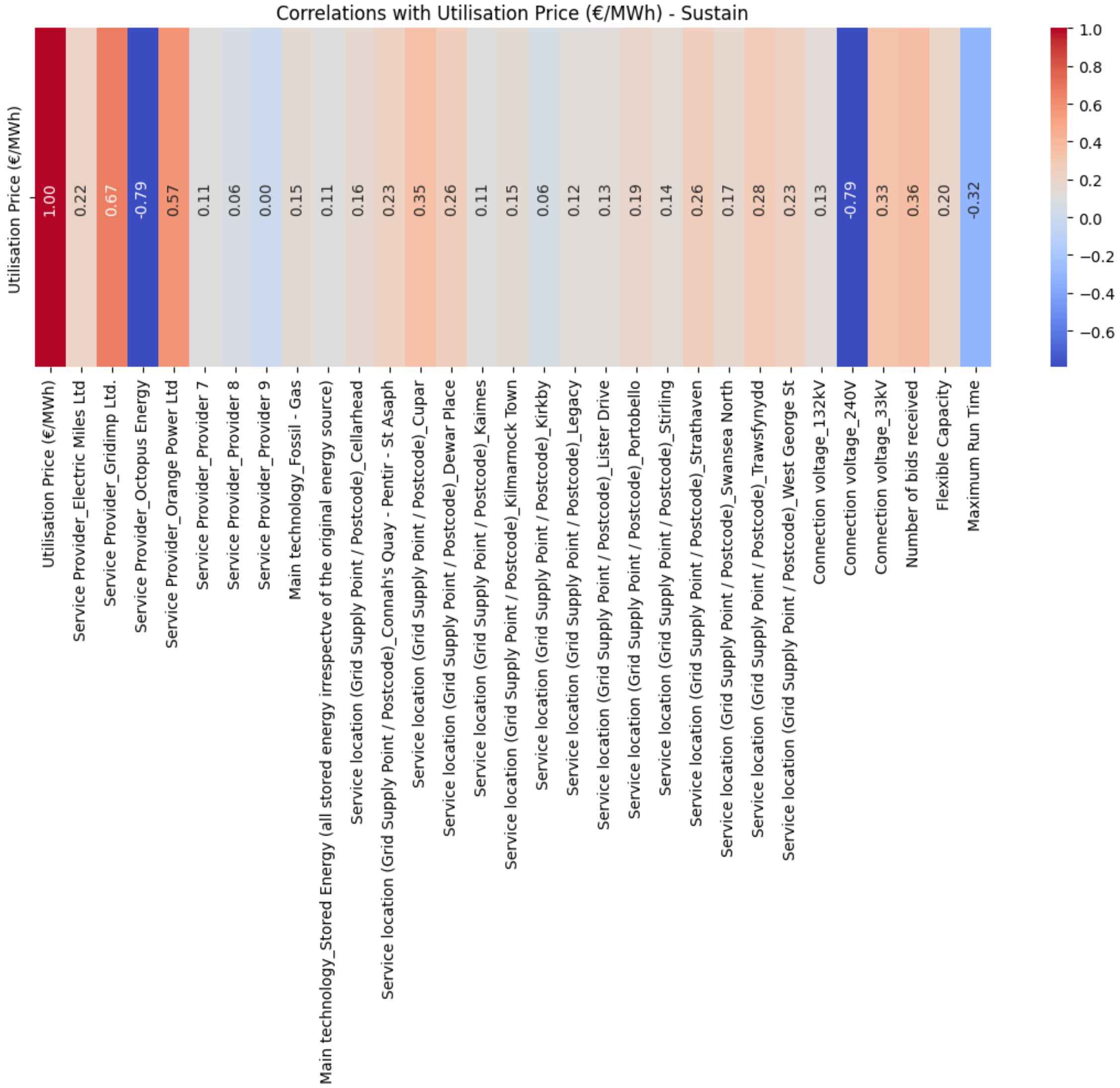

Figure 24: Correlations with utilisation price for Sustain product

The results of the correlation matrix indicate that some variables show stronger correlations with the utilisation price, such as provider or voltage. These correlations suggest that these variables could have a notable impact on the variability of utilisation prices.

The utilisation price regression model for the Sustain product is presented below, which will allow a deeper understanding of the factors influencing price formation in the local service markets of the system. Table 10 and Table 11 show the results of this model.

Model Results for Utilisation Price (€/MWh)

Table 10: Overall results of Sustain's utilisation price model

Description	Value
Dependent Variable	Utilisation Price (€/MWh)
Model	OLS
Method	Least Squares
R-squared	0.946
Adjusted R-squared	0.945
F-statistic	1994.0
Prob (F-statistic)	0.00

Table 11: Coefficients of Sustain's utilisation price model

Variable	coef	std err	t	P>|t|
const	-1.83e+13	3.73e+13	-0.49	0.624
Service Provider_Electric Miles Ltd	1.83e+13	3.73e+13	0.49	0.624
Service Provider_Gridimp Ltd.	1.83e+13	3.73e+13	0.49	0.624
Service Provider_Octopus Energy	1.83e+13	3.73e+13	0.49	0.624
Service Provider_Orange Power Ltd	1.83e+13	3.73e+13	0.49	0.624
Service Provider_Provider 7	9.14e+12	1.87e+13	0.49	0.624
Service Provider_Provider 8	-6.6212	14.13	-0.469	0.639
Service Provider_Provider 9	1.83e+13	3.73e+13	0.49	0.624
Main technology_Fossil - Gas	1.83e+13	3.73e+13	0.49	0.624
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	9.14e+12	1.87e+13	0.49	0.624
Service location (Grid Supply Point / Postcode)_Cellarhead	-104.3438	12.396	-8.417	0.0

Service location (Grid Supply Point / Postcode)_Connah's Quay - Pentir - St Asaph	-175.3625	14.271	-12.288	0.0
Service location (Grid Supply Point / Postcode)_Cupar	-111.0453	11.885	-9.343	0.0
Service location (Grid Supply Point / Postcode)_Dewar Place	-122.5782	12.115	-10.118	0.0
Service location (Grid Supply Point / Postcode)_Kaimes	44.1831	15.919	2.775	0.006
Service location (Grid Supply Point / Postcode)_Kilmarnock Town	-118.9195	15.208	-7.819	0.0
Service location (Grid Supply Point / Postcode)_Kirkby	33.4685	18.111	1.848	0.065
Service location (Grid Supply Point / Postcode)_Legacy	-109.612	17.226	-6.363	0.0
Service location (Grid Supply Point / Postcode)_Lister Drive	213.6805	44.323	4.821	0.0
Service location (Grid Supply Point / Postcode)_Portobello	-126.7723	13.717	-9.242	0.0
Service location (Grid Supply Point / Postcode)_Stirling	-172.3431	14.147	-12.182	0.0
Service location (Grid Supply Point / Postcode)_Strathaven	-122.576	12.115	-10.118	0.0
Service location (Grid Supply Point / Postcode)_Swansea North	-121.7024	14.187	-8.579	0.0
Service location (Grid Supply Point / Postcode)_Trawsfynydd	-116.8782	12.243	-9.547	0.0
Service location (Grid Supply Point / Postcode)_West George St	-124.0797	12.694	-9.775	0.0
Connection voltage_132kV	-323.1484	42.84	-7.543	0.0

Connection voltage_240V	-141.6372	11.485	-12.333	0.0
Connection voltage_33kV	-174.9816	10.401	-16.824	0.0
Number of bids received	-2.6525	0.851	-3.115	0.002
Flexible Capacity	11.0834	2.194	5.052	0.0
Maximum Run Time	-3.7361	0.473	-7.896	0.0

In case of sustain product, numerous variables are significant, as is the case for almost all locations (93%), the voltage, the number of bids received, the flexible capacity, or the maximum run time. The coefficients associated with the voltage are interesting, since high voltage values lead to a significant decrease in price. Again, the coefficients of the various locations are also important, so a multivariate regression model is now performed for each location to analyze why the different locations have such price differences. The results of the different models are shown in Figure 25:

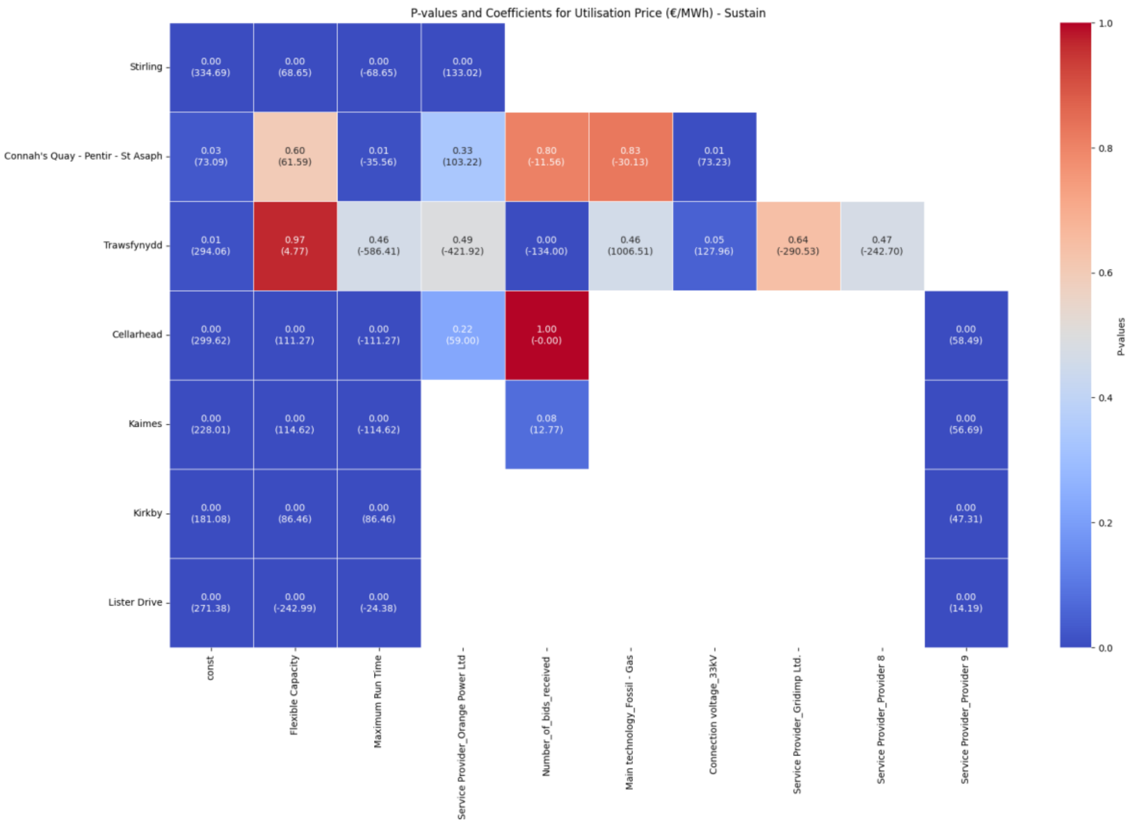

Figure 25: Location regression models for utilisation price for Sustain product

In case of utilisation price for sustain, in 3 out of 7 locations, or 43% of the locations, the significant variable with the greatest impact on price was the flexible capacity, suggesting that, in these locations, the amount of flexible capacity offered by providers is a crucial factor in determining utilisation prices. In the remaining locations, the number of bids, the maximum run time, the voltage, and the provider were the variable with the greatest impact on price at a location. Technology type was not significant for any location.

As before, it should be noted that there are certain locations where the regression model could not be calculated because there was insufficient data to calculate it or because of the lack of variation in the data. For these cases, the average utilisation price in these locations is plotted in Figure 26 against the overall average utilisation price of the Sustain product, identifying these locations as some of the outliers mentioned above, with a price substantially higher than the average price.

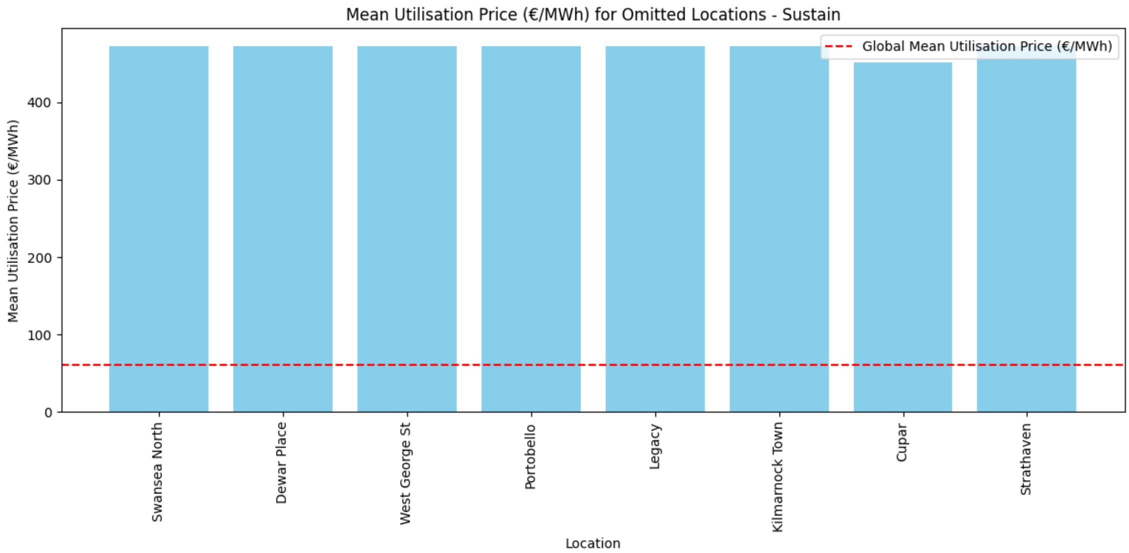

Figure 26: Mean utilisation price for omitted locations for Sustain product

4.4 Dynamic product

4.4.1 Availability price

First, the variation and dispersion in the availability prices of the Dynamic product is analyzed:

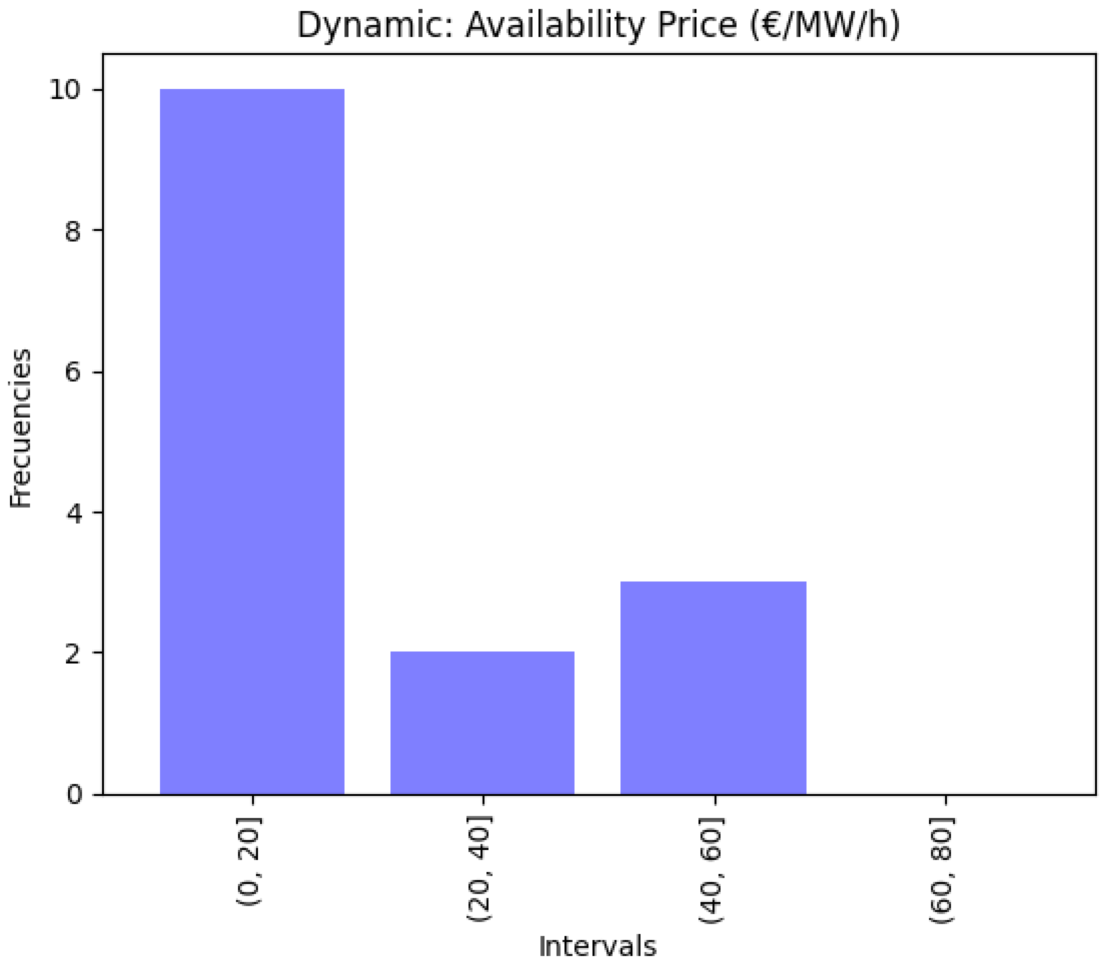

Figure 27: Histogram of Dyanmic's availability prices

Figure 28: Boxplot of Dynamic's availability prices

The histogram (Figure 27) shows how availability prices are distributed and the variation of these prices for the Dynamic product, with the prices being quite low, generally below 20 €/MW/h, but with prices also ranging between 40 and 60 €/MW/h.

The boxplot (Figure 28), on the other hand, provides a more detailed view of the variation of availability prices in line with the above. In addition, the average availability price for this product, which is 17.40 €/MW/h, is also shown.

As in the previous cases, in order to explain the variability and dispersion of prices and to analyze the factors that may affect them, a multivariate regression model has been carried out in which the same variables as in the rest of the products have been included.

As a preliminary analysis, the correlations between the availability price and the different variables were obtained, as shown in Figure 29.

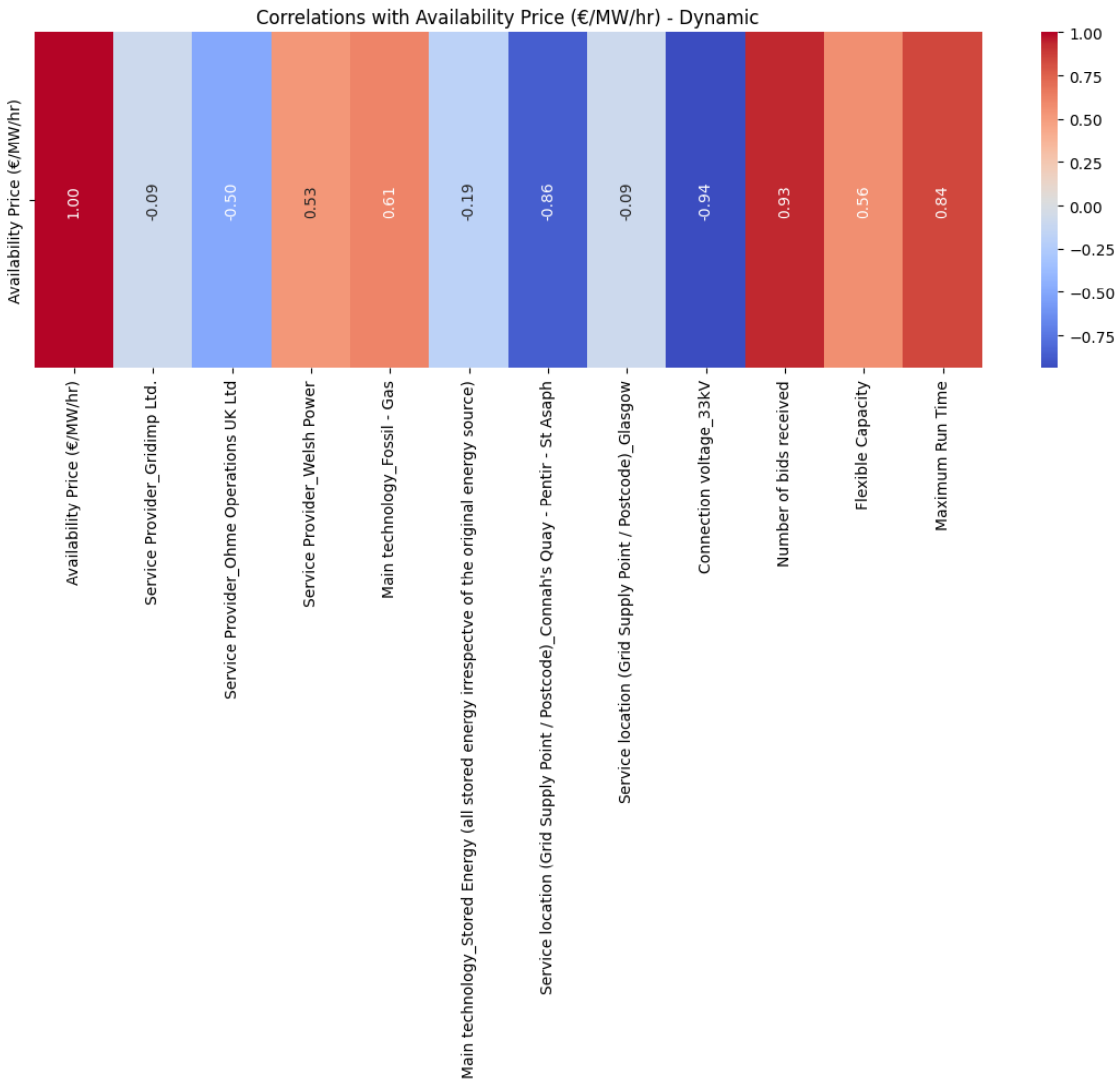

Figure 29: Correlations with availability price for Dynamic product

The results of the correlation matrix indicate a generally strong correlation of all variables with availability price, although this may be due to the limited data available for this product (only 15 observations).

The availability price regression model for the Dynamic product is now presented, which allows a deeper understanding of the factors influencing price formation for this product. Table 12 and Table 13 show the results of this model.

Model Results for Availability Price (€/MW/hr)

Table 12: Overall results of Dynamic's availability price model

Description	Value
Dependent Variable	Availability Price (€/MW/hr)
Model	OLS
Method	Least Squares
R-squared	0.923
Adjusted R-squared	0.826
F-statistic	9.541
Prob (F-statistic)	0.0242

Table 13: Coefficients of Dynamic's availability price model

Variable	coef	std err	t	P>|t|
const	9.1586	3.431	2.67	0.056
Service Provider_Gridimp Ltd.	-3.6214	10.723	-0.338	0.753
Service Provider_Ohme Operations UK Ltd	5.056e-15	6.07e-15	0.834	0.451
Service Provider_Welsh Power	-6.2293	11.973	-0.52	0.63
Main technology_Fossil - Gas	12.5115	8.425	1.485	0.212
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	0.2685	4.957	0.054	0.959

Service location (Grid Supply Point / Postcode)_Connah's Quay - Pentir - St Asaph	5.203	9.494	0.548	0.613
Service location (Grid Supply Point / Postcode)_Glasgow	-3.6214	10.723	-0.338	0.753
Connection voltage_33kV	1.5816	1.646	0.961	0.391
Number of bids received	23.9935	14.056	1.707	0.163
Flexible Capacity	-13.4898	15.808	-0.853	0.442
Maximum Run Time	0.4784	4.327	0.111	0.917

None of the variables included in the model is significant, so the impact of these variables on the price cannot be determined in this case. As mentioned above, the lack of data may be the cause of this effect.

In addition, in none of the locations for this product was it possible to estimate the regression model because there was insufficient data to estimate it or because of the lack of variation in the data. For these cases, only the average price of availability in these locations is plotted in Figure 30 against the overall average price of availability of the Dynamic product. It can be seen how the high availability prices for this product correspond to the Carrington - Fiddlers Ferry location.

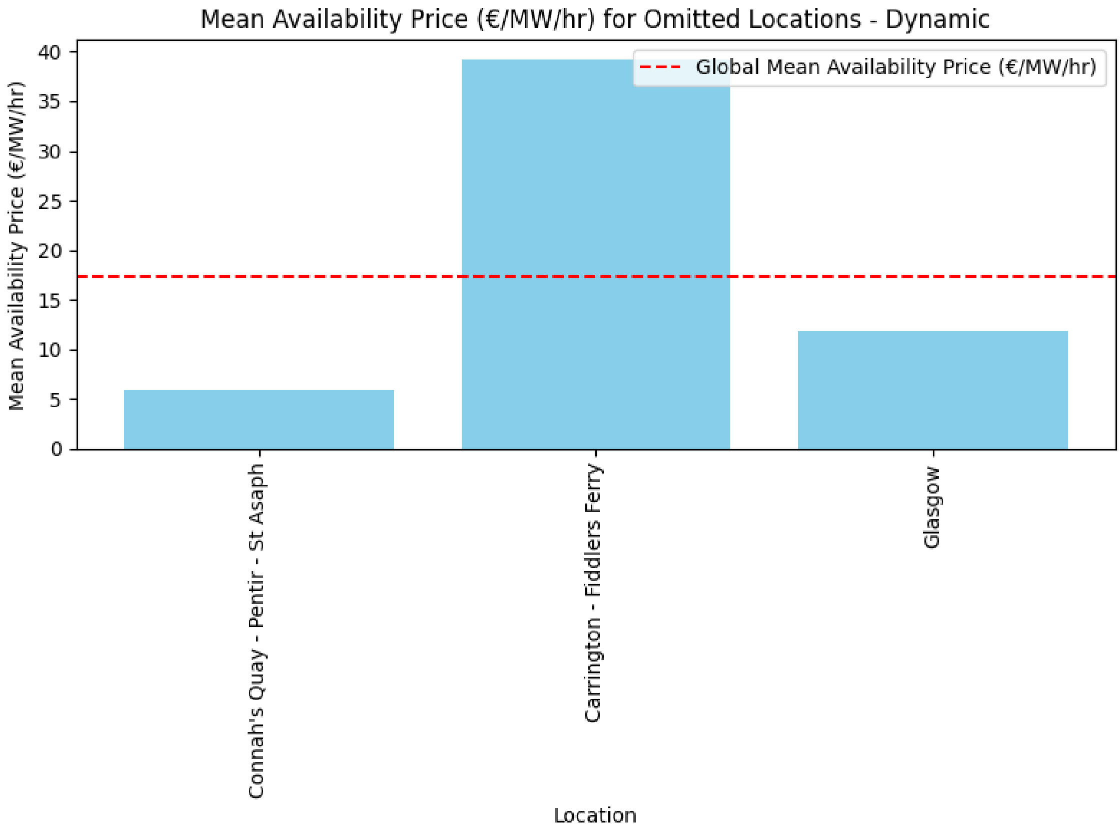

Figure 30: Mean availability price for omitted locations for Dynamic product

4.4.2 Utilisation Price

Again, first, the variation and dispersion in the utilisation prices of the Dynamic product is analyzed:

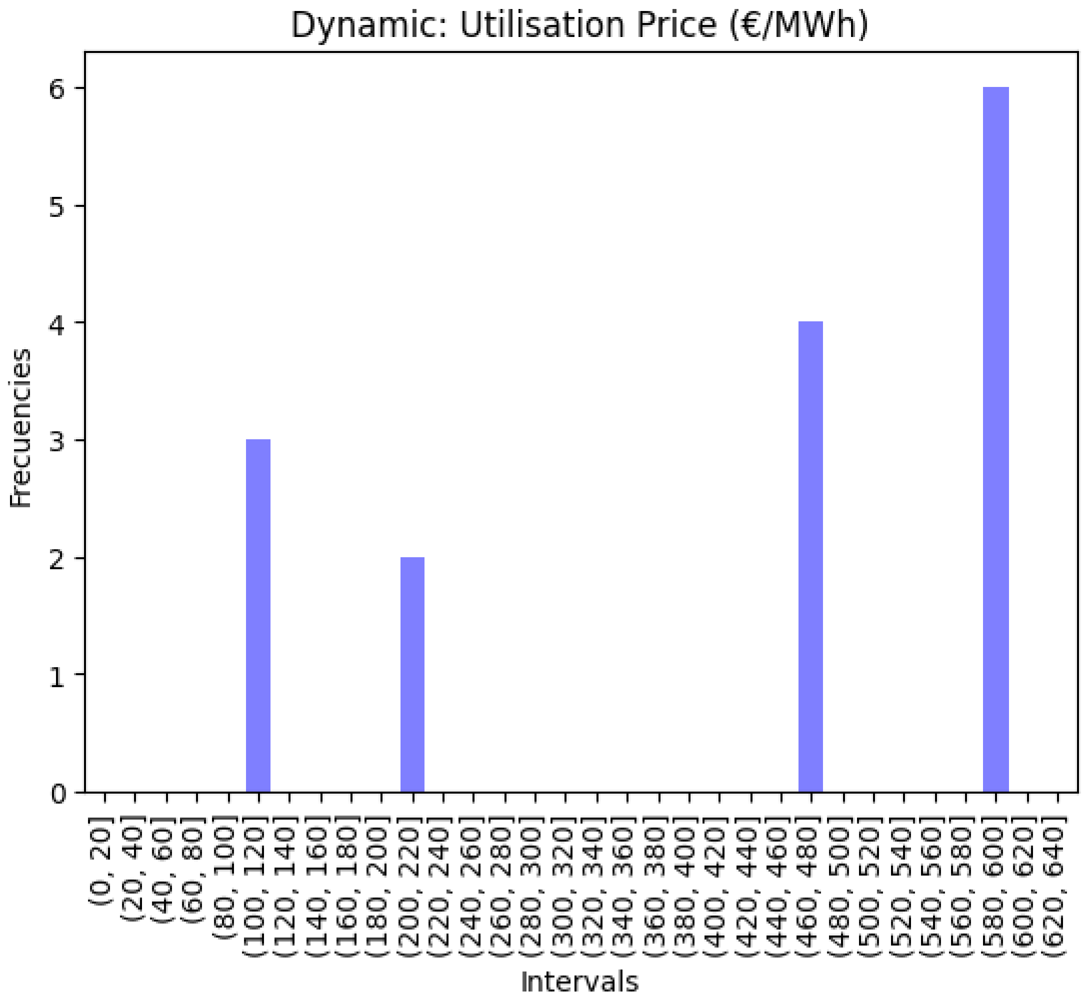

Figure 31: Histogram of Dynamic's utilisation prices

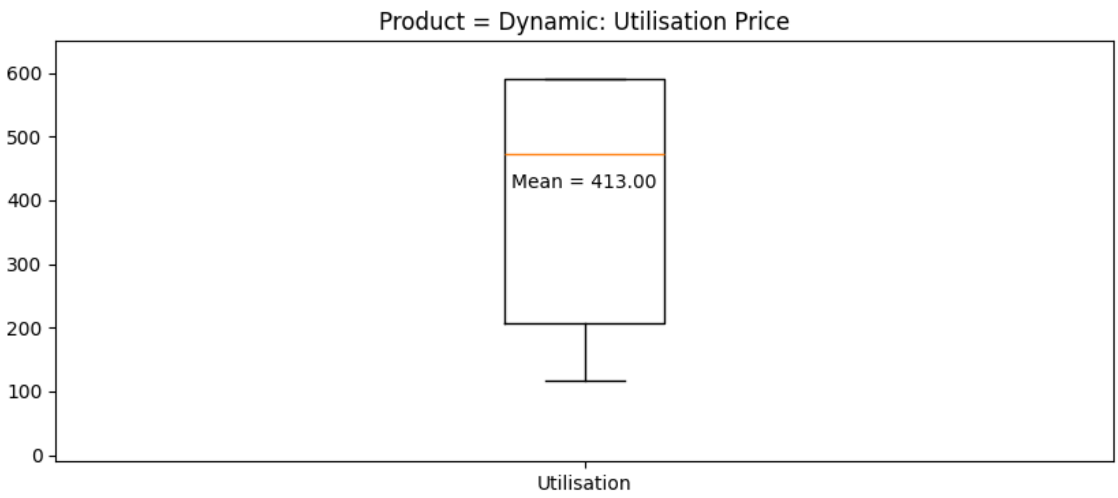

Figure 32: Boxplot of Dynamic's utilisation prices

The histogram (Figure 31) shows how the utilisation prices for the Dynamic product are distributed, with very varied prices ranging from 100 €/MWh to 600 €/MWh, thus presenting a significant price dispersion.

The boxplot (Figure 32) again reflects this variation in utilisation prices, which shows an average price of 413.00 €/MWh, much higher than in all previous cases.

Following the same procedure, a multivariate regression model is carried out with the same variables as in the other cases to analyze the factors that can affect prices.

As a preliminary analysis, the correlations between the utilisation price and the different variables were obtained, as shown in Figure 33.

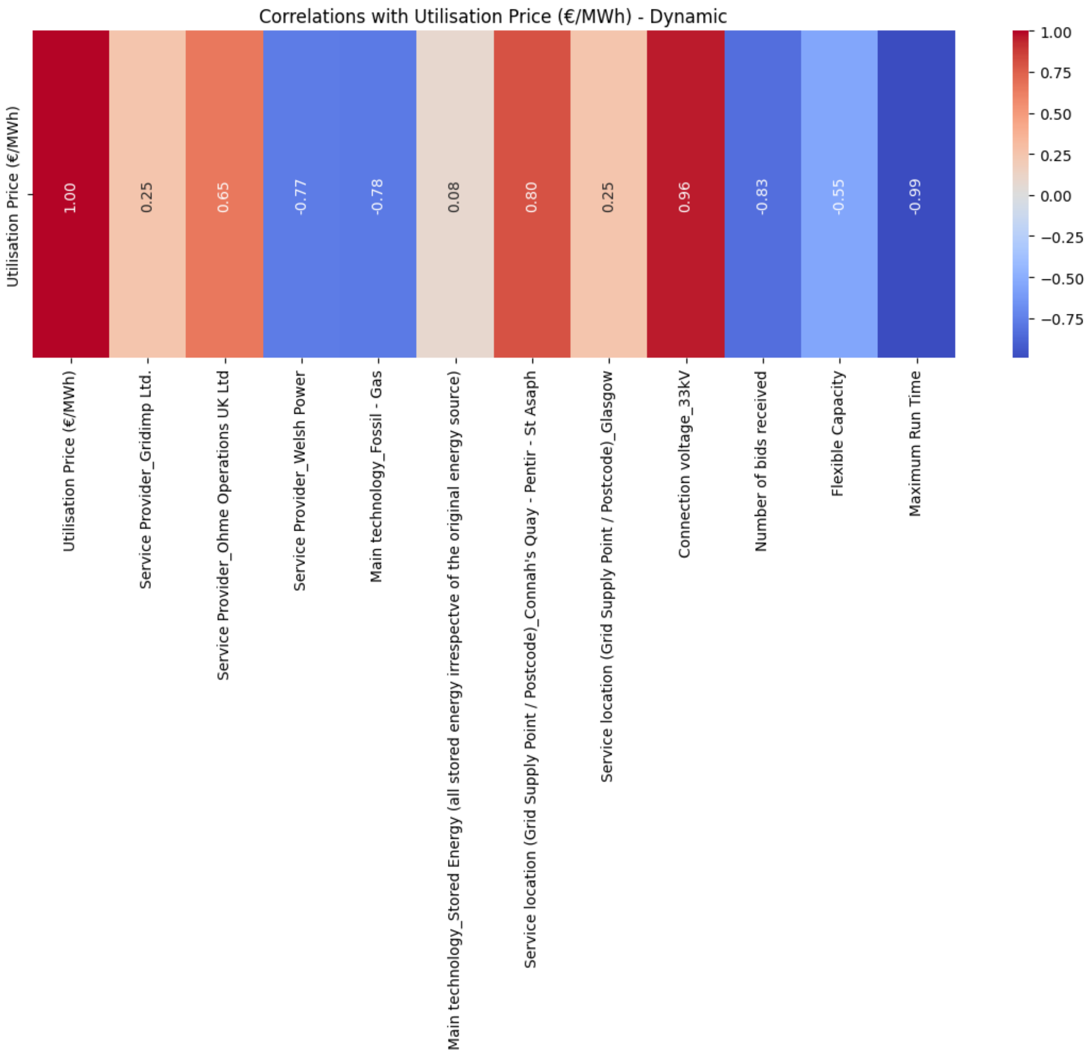

Figure 33: Correlations with utilisation price for Dynamic product

As with the availability price, the results of the correlation matrix indicate a generally strong correlation of all variables with the utilisation price. Again, the limited data available for this product may account for this.

The utilisation price regression model for the Dynamic product is now presented, which allows a deeper understanding of the factors influencing price formation for this product. Table 14 and Table 15 show the results of this model.

Model Results for Utilisation Price (€/MWh)

Table 14: Overall results of Dynamic's utilisation price model

Description	Value
Dependent Variable	Utilisation Price (€/MWh)
Model	OLS
Method	Least Squares
R-squared	1.0
Adjusted R-squared	1.0
F-statistic	5.664e+29
Prob (F-statistic)	8.73e-60

Table 15: Coefficients of Dynamic's utilisation price model

Variable	coef	std err	t	P>|t|
const	174.7445	1.49e-13	1.17e+15	0.0
Service Provider_Gridimp Ltd.	86.9581	4.65e-13	1.87e+14	0.0
Service Provider_Ohme Operations UK Ltd	-1.189e-14	2.63e-28	-4.52e+13	0.0
Service Provider_Welsh Power	8.3956	5.19e-13	1.62e+13	0.0
Main technology_Fossil - Gas	49.1686	3.65e-13	1.35e+14	0.0
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	38.6178	2.15e-13	1.8e+14	0.0

Service location (Grid Supply Point / Postcode)_Connah's Quay - Pentir - St Asaph	39.3692	4.12e-13	9.56e+13	0.0
Service location (Grid Supply Point / Postcode)_Glasgow	86.9581	4.65e-13	1.87e+14	0.0
Connection voltage_33kV	126.3272	7.14e-14	1.77e+15	0.0
Number of bids received	22.4202	6.09e-13	3.68e+13	0.0
Flexible Capacity	-6.111e-13	6.85e-13	-0.892	0.423
Maximum Run Time	-107.2057	1.88e-13	-5.71e+14	0.0

For dynamic utilisation price, all the variables considered are significant, with the exception of flexibility capacity. The variables with the greatest impact on price are voltage and maximum run time, although the rest of the variables also have an impact.

A multivariate regression model is again performed for each of the locations to analyze the reasons for the price differences between the different zones. The results of the different models are shown in Figure 34.

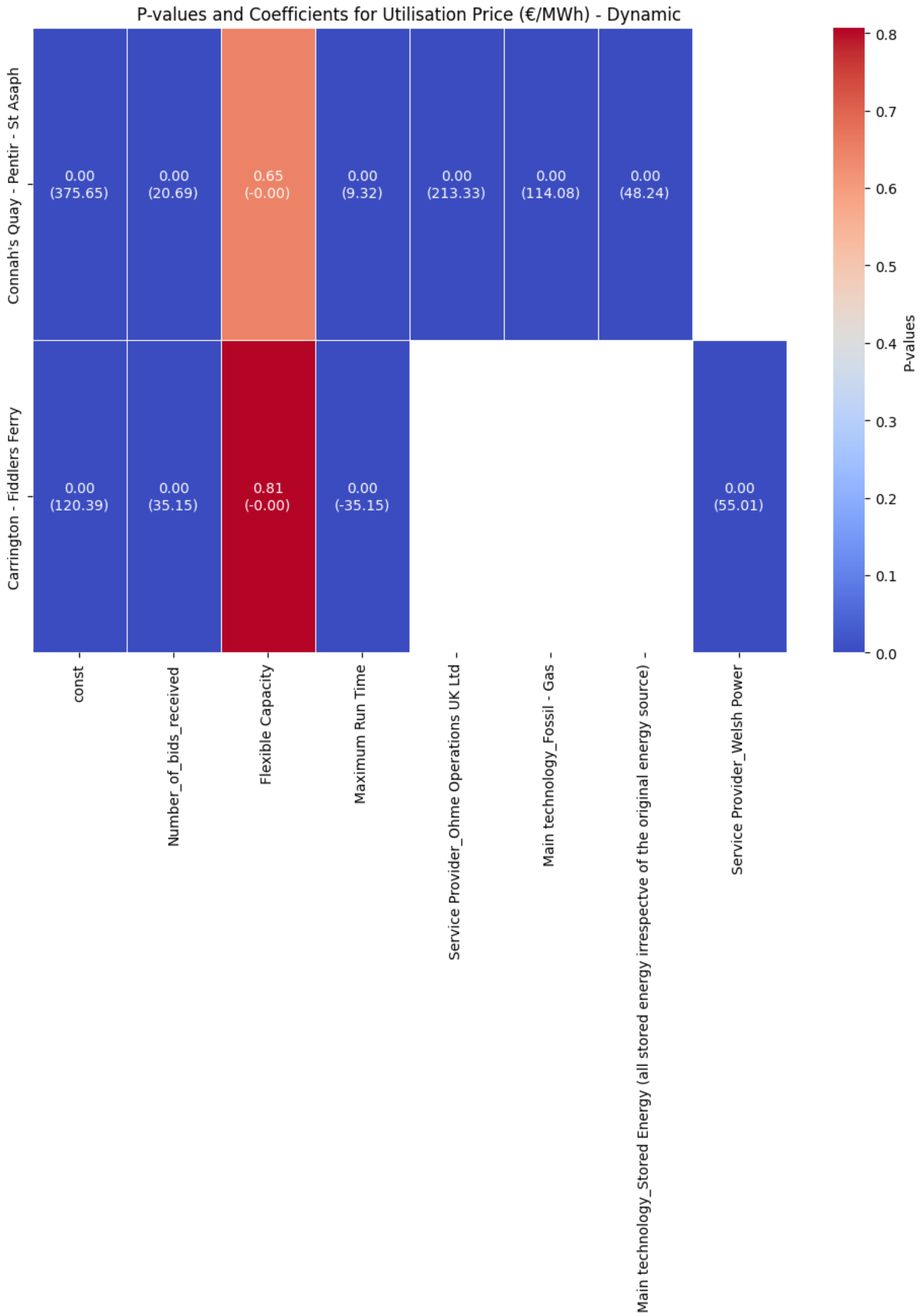

Figure 34: Location regression models for utilisation price for Dynamic product

In the 2 locations where the model was calculated, the provider is the significant variable with the greatest impact on price, which again suggests that the provider is a crucial factor in determining prices, in this case, utilisation prices.

As was the case in the other products, in this case there is one location where the regression model could not be calculated because there was insufficient data to calculate it. The average utilisation price at this location is therefore plotted in Figure 35 against the overall average utilisation price of the Dynamic product. It can be seen how the utilisation price for this location (Glasgow) is higher than the average price.

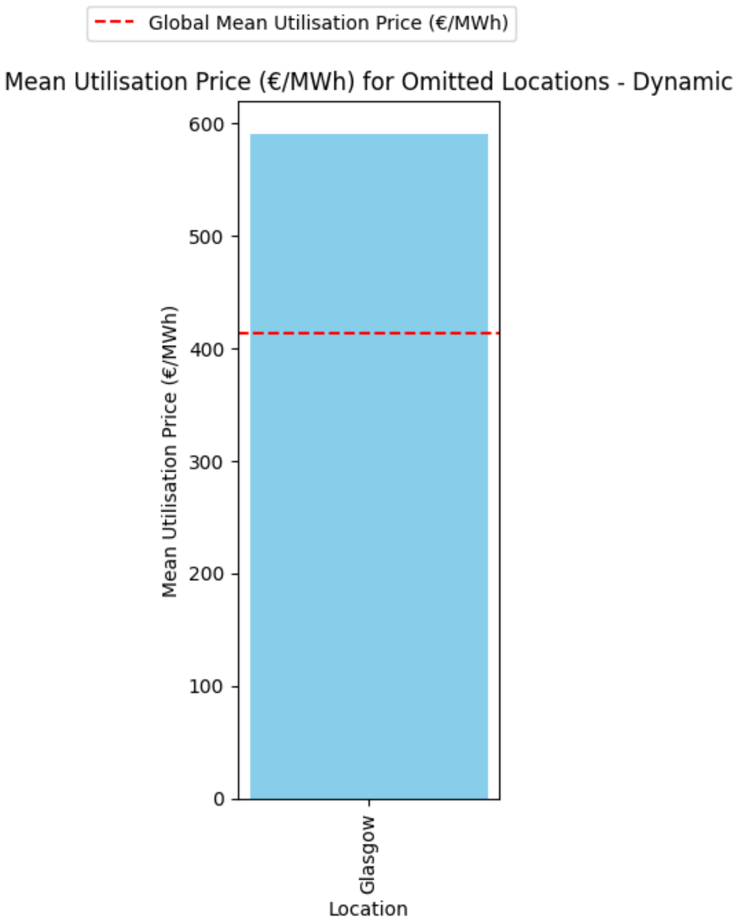

Figure 35: Mean utilisation price for omitted location for Dynamic

4.5 Restore product

4.5.1 Utilisation Price

The Restore product, as explained in the state of the art, is only paid per use, so the analysis is simply carried out for this case. First, the variation and dispersion in the utilisation prices of the Restore product is analyzed:

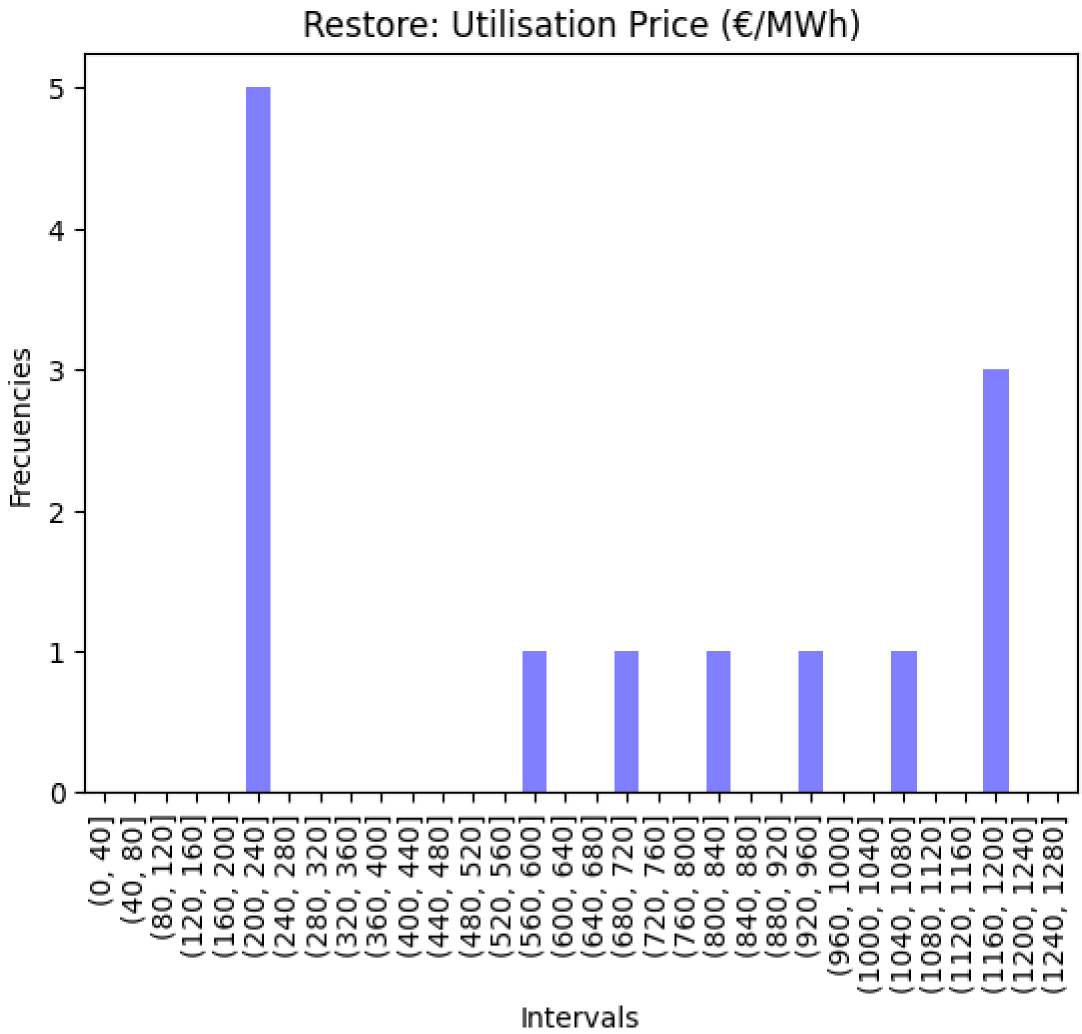

Figure 36: Histogram of Restore's utilisation prices

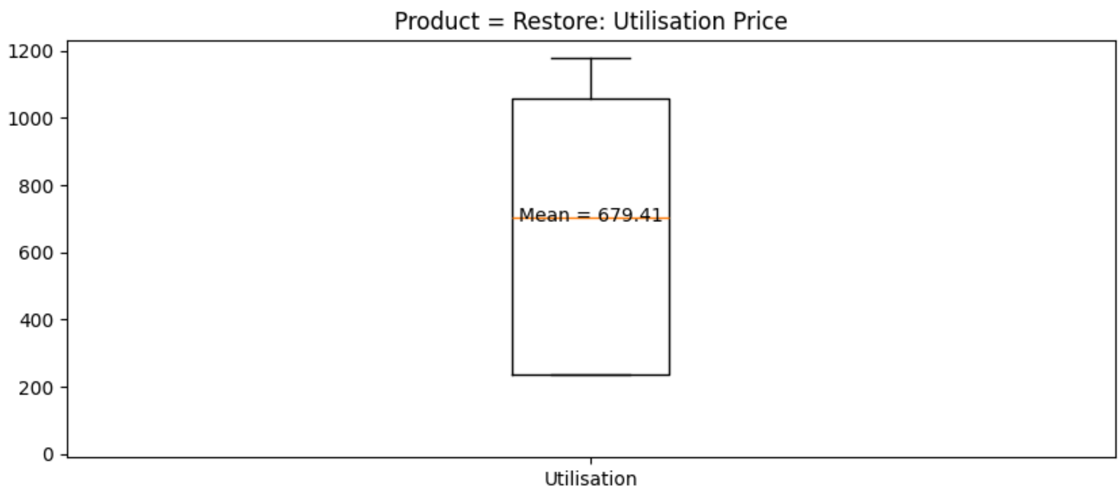

Figure 37: Boxplot of Restore's utilisation prices

The histogram (Figure 36) shows how the utilisation prices for the Restore product are distributed, with prices widely spread between €200 and €1200/MWh, with a large dispersion in prices.

The boxplot (Figure 37) again reflects this variation in utilisation prices, with an average price of 679.41 €/MWh, the highest of all products.

To explain the price variability and analyze the factors that can affect prices, a multivariate regression model is again performed. First, as a preliminary analysis, the correlations between the utilisation price and the different variables have been obtained, as shown in Figure 38.

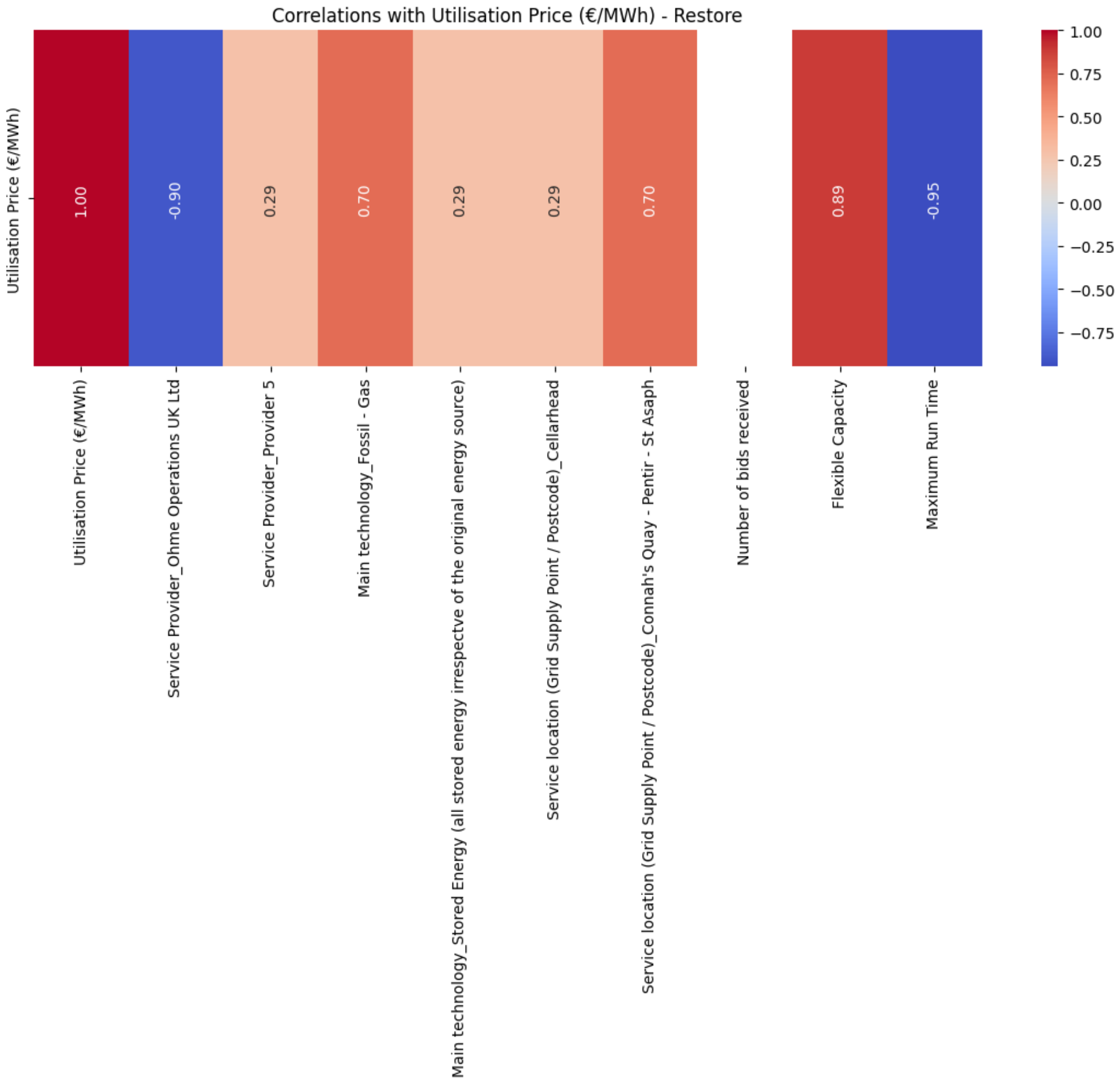

Figure 38: Correlations with utilisation price for Restore product

As was the case for the Dynamic product, the results of the correlation matrix indicate a generally strong correlation of all variables with the utilisation price, as again there are few data available for this product (13 observations only).

The utilisation price regression model for the Restore product is now presented, which will allow a deeper understanding of the factors influencing price formation for this product. Table 16 and Table 17 show the results of this model.

Model Results for Utilisation Price (€/MWh)

Table 16: Overall results of Restore's utilisation price model

Description	Value
Dependent Variable	Utilisation Price (€/MWh)
Model	OLS
Method	Least Squares
R-squared	0.965
Adjusted R-squared	0.953
F-statistic	82.16
Prob (F-statistic)	7.37e-07

Table 17: Coefficients of Restore's utilisation price model

Variable	coef	std err	t	P>|t|
const	400.3298	18.923	21.156	0.0
Service Provider_Ohme Operations UK Ltd	-46.9724	45.74	-1.027	0.331
Service Provider_Provider 5	131.0069	18.714	7.0	0.0
Main technology_Fossil - Gas	316.2952	25.864	12.229	0.0
Main technology_Stored Energy (all stored energy irrespectve of the original energy source)	131.0069	18.714	7.0	0.0
Service location (Grid Supply Point / Postcode)_Cellarhead	131.0069	18.714	7.0	0.0
Service location (Grid Supply Point /	316.2952	25.864	12.229	0.0

Postcode)_Connah's Quay - Pentir - St Asaph				
Number of bids received	0.0	0.0	nan	nan
Flexible Capacity	-390.1356	130.045	-3.0	0.015
Maximum Run Time	-482.1545	87.853	-5.488	0.0

Practically all the variables that appear in the model are significant, and their coefficients are generally quite high, so they have a great impact on the price. In this case, the coefficient associated with the number of bids received is not calculated due to the lack of variation in the data for this variable.

In addition, in none of the locations for this product was it possible to calculate the regression model because there was insufficient data to calculate it or because of the lack of variation in the data. For these cases, only the average utilisation price at these locations is plotted in Figure 39 against the overall average utilisation price of the Restore product. It can be seen how, at the Cellarhead and, especially, Connah's Quay - Pentir - St Asaph locations, the prices are very high, and at Braehead Park they are substantially lower and moderate.

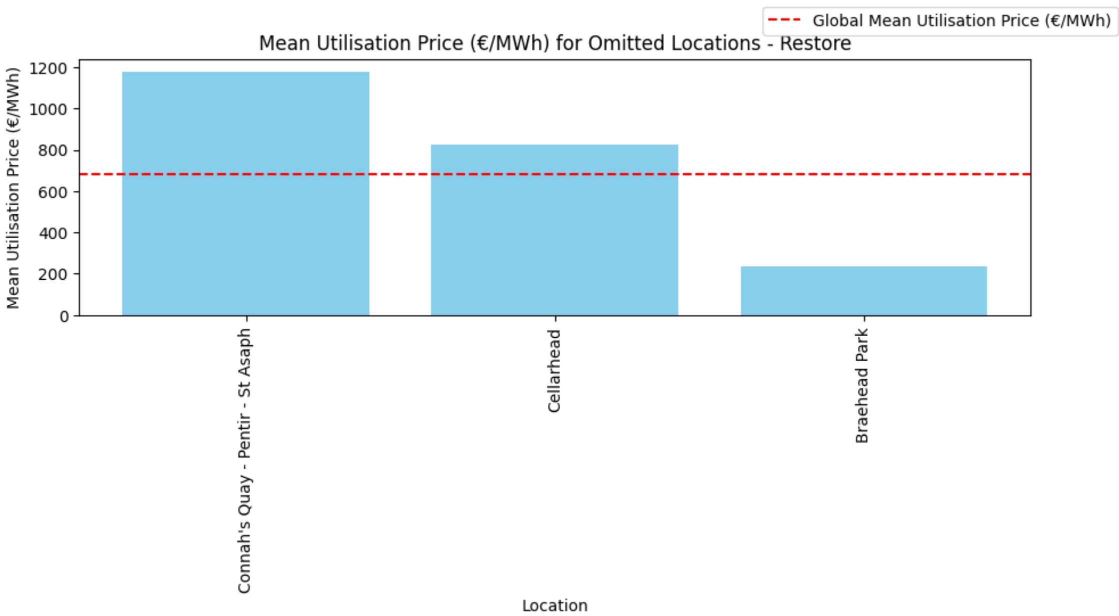

Figure 39: Mean utilisation prices for omitted locations for Restore product

4.6 Results summary

The multivariate regression models developed allowed us to identify those variables that have the greatest impact on both availability and utilisation prices. The results of the models are summarized in Table 18 and Table 19, which show the number of locations, in percentage, in which the variable in question had the greatest impact on price by type of product.

Table 18: No. of locations (%) in which the variable had the greatest impact on availability price by product type

Availability Price €/MW/h	Provider	Voltage	Technology	No. of bids received	Flexible Capacity	Maximum Run Time
Secure	76.25%	4.75%	0%	9.50%	4.75%	4.75%
Sustain	-	-	-	-	-	-
Dynamic	N	O	D	A	T	A
Restore	-	-	-	-	-	-

Table 19: No. of locations (%) in which the variable had the greatest impact on utilisation price by product type

Utilisation Price €/MWh	Provider	Voltage	Technology	No. of bids received	Flexible Capacity	Maximum Run Time
Secure	63.75%	9%	4.50%	13.75%	4.50%	4.50%
Sustain	14.25%	14.25%	0%	14.25%	43%	14.25%
Dynamic	100%	0%	0%	0%	0%	0%
Restore	N	O	D	A	T	A

One possible hypothesis that could explain the differences observed between the various products could be based on the technical and operational characteristics that define them. For example, products such as Secure, whose priority is based on stability and reliability, may show a greater dependence on the experience and capacity of the provider. In contrast, products such as Sustain, designed with the objective of leveraging flexibility, may rely more heavily on available flexible capacity.

These observations suggest that, within the system services market, each product has a specific niche influenced by both its technical and operational requirements. This qualitative analysis opens the door to future research that could formalize these hypotheses and explore in more detail the reasons behind the variability in the relevance of different dimensions for each product.

5. Conclusions

This section presents the main findings of the analyses conducted in the local system services markets, specifically with regard to market competitiveness and price determinants of flexibility products.

The market competitiveness analysis and study revealed high concentration in the system services market, with a HHI of 7237.84. This number represents a market structure in which there are few large providers, or in other words, very little competition. When the HHI was broken down by product type, the differences in the level of market concentration were quite evident: the Sustain product had the highest concentration, while the Secure product had the lowest concentration relative to the other products examined.

In addition, through the analysis of competitiveness by location, it was concluded that most of the locations have a very high concentration, with an HHI above 5000. This implies, therefore, that the system services market is, again, strongly dominated by a few providers, a fact that could have strong implications in terms of efficiency and stability of the electricity system. The fact of depending on a few providers makes the system more vulnerable in the event that one of these providers faces technical problems.

The high concentration in the system services market is a sign that pro-competitive policies are needed. These policies could include, for example, incentives for the entry of new providers and support for technologies that allow for a more diversified and decentralized provision of flexibility services. In addition, high concentration may not be beneficial for innovation and efficiency in the provision of flexibility services.

Regarding regression models, Table 18 and Table 19 show how, in most cases, the provider is the variable with the greatest impact on prices, as is the case for Secure and Dynamic products. In fact, the identity of the provider was a decisive element in determining both availability and utilisation prices in many locations. This could be due to differences in experience, operational efficiency or pricing strategies among vendors. Also, competition among providers can be a powerful influence in terms of pricing, and larger providers may have more room to raise prices given their larger market share.

For Sustain product, flexible capacity was the significant variable with the greatest influence on utilisation price in 43% of the locations, meaning that, in those locations, the amount of flexible capacity that providers offer is a determining factor in utilisation price. Providers with more capacity could have greater bargaining power to charge higher prices because of the scale of the services they can provide. In addition, having more flexible capacity allows the system operator to more efficiently manage energy needs and availability, which is absolutely critical to solve network constraints.

Ultimately, these findings reflect and highlight the need for increased provider diversification in the market. Both regulators and system operators should consider different measures in order to prevent the market power of large providers and increase the role of small and medium-sized players. Flexible capacity has also proven to be a key variable in price formation. This is why investments to increase available flex capacity, through infrastructure development and investments in advanced technologies, can contribute to stabilizing and reducing tariffs for flex services.

In conclusion, through this analysis, a detailed understanding of the mechanisms of local markets for system services, as well as the determinants of price formation, has been revealed. Recommendations based on these findings can help to achieve a more competitive, efficient and sustainable electricity market that benefits both electricity suppliers and consumers, thus supporting the evolution towards a more resilient and sustainable electricity system.

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Appendix: Alignment with Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a universal call to action adopted by all member states of the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development. The SDGs are an agenda that addresses the most pressing issues facing humanity, including eradicating poverty, protecting the planet or ensuring peace and prosperity for all. In total, 17 goals were established, with each presenting specific targets to be achieved over the next 15 years [36]

This work aligns with several of these SDGs in a significant way, especially with the following goals:

- **Goal 7: Affordable and clean energy**

  This goal aims to ensure access to affordable, reliable, sustainable and modern energy for everyone. This goal is also fundamental to progress in other areas of sustainable development, including health, education, industry and climate change mitigation. The study of local markets for system services aligns with this goal by improving and facilitating the inclusion of distributed energy resources and renewable energies in the electricity system. By involving flexibility markets in these resources, operational efficiency in the electricity system is increased along with the share of renewables in the energy mix. In addition, local markets for system services also allow energy access to be more equitable and distributed, benefiting those communities that have usually been underserved due to centralized infrastructure.

- **Goal 9: Industry, innovation and infrastructure**

  The purpose of this goal is based on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. This goal also recognizes that infrastructure investment is important to achieve goals such as sustainable development and community empowerment. By improving infrastructure related to both energy distribution and consumption and fostering innovation in the energy sector, this work contributes to this goal. By analyzing and optimizing local markets for system services, it contributes to advancing the development of new technologies and practices capable of improving both the efficiency and resilience of energy infrastructure. This includes using digital solutions, such as Piclo, to facilitate the deployment of market participation and support the incorporation of advanced technologies to manage energy supply and demand.

- **Goal 11: Sustainable cities and communities**

This goal aims to make cities and human settlements inclusive, safe, sustainable and resilient. The overall objective of this goal is based on solving the problems associated with urbanization, by promoting cities with opportunities available to all, as well as access to basic services such as energy, housing, transportation... The development of a much more distributed electricity system and the creation of local markets for system services undoubtedly contribute to this goal, as they promote the sustainability of both cities and communities. Local markets for system services also allow stronger participation of communities in the production and consumption of energy, with benefits for the resilience of the energy infrastructure and thus achieving less dependence on large power plants.

- **Goal 13: Climate action**

Climate change is one of the biggest problems in the world today, affecting all countries and all people in one way or another. The immediate need to combat climate change and its effects is the main theme of this goal. Research into local markets for system services is particularly important to this goal by enabling the integration of renewable energies and improving the efficiency of the electricity system, thereby reducing greenhouse gas emissions. By enabling the effective participation of distributed energy resources and facilitating flexibility in both energy generation and consumption, the effects of climate change are reduced, and the power system becomes more resilient to adverse weather events.

Figure 40: Sustainable Development Goals aligned with work