Reforming the UK Energy Market for Sustainable Development: Integrating Renewables, Fair Pricing, and Demand-Side Response

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Abstract

The aim of this study is to propose reforms that align the UK energy market with sustainability goals, specifically focusing on integrating renewable energy sources, establishing fair pricing structures, and implementing demand-side response measures. This research exposes the systematic challenges in the existing market structure that prevent sustainability, through policy analysis, case studies and interviews. Despite the progress in renewable energy technologies, the UK energy market faces structural and regulatory challenges that hinder the seamless integration of renewables. Therefore, the reform framework presented in this paper calls for a synchronised overhaul of market signalisation, which includes integration of locational marginal pricing, advanced capacity markets, and standardised demand response methods. In addition, this paper provides insights into the theoretical tenets underpinning energy transitions as well as a policy guidance into how to balance competing objectives while achieving the overall objective of decarbonization. The dissertation argues, therefore, that market reform entails the crafting of coherent policy packages across previously insulated fields and a rigorous comparative assessment of effects on distribution and sequence of policy enactment.

Chapter 1:

Introduction

1.1 Background to the Study

According to Bettarelli et al. (2024), the structure of the UK energy market has changed significantly since the process of market liberalisation started in the 1990s. Thus, what was initially conceived as a mere privatisation initiative has morphed into a delicate web of markets and regulations, policy measures and tools that seek to reconcile the goals of affordability, security, and sustainability. The Climate Change Act 2008 provides the basis for legally binding carbon reduction targets, while subsequent policies such as the Electricity Market Reform (EMR), the Smart Meter Implementation Programme, and the Energy White Paper have sought to reform markets for their decarbonisation (Dubash, 2003). All the same, the UK energy market remains problematic even in the face of such reforms. The system was originally intended for centralised fossil fuel power stations with operational plans that could be easily scheduled in advance, not for the variable generation that is increasingly popular today (Dubash, 2003). Therefore, the current organisation of wholesale electricity markets relying on primarily marginal price signals is insufficient to stimulate investments in capital-intensive renewable technologies with negligible marginal costs. Competition in the retail markets also has centered on price with little developments in service offerings that could realistically fulfill the sustainability goals.

The events of the COVID-19 pandemic and the subsequent energy price fluctuance of 2021-22 exposed these strategic flaws in the design of the liberalised market, with concerns relating to system resilience, affordability and the social relevance of energy (Cabot & Villavicencio, 2024). Climate deadlines, alongside questions of energy security and cost, means that the argument for holistic market transformation is no longer a nice-to-have but a must-have to meet the UK's sustainable development goals. Nahhas and Ibhadode (2022) argued that with the development of the solar and wind technologies, these resources have become feasible and could effectively contribute to the national energy mix. Specifically in the UK, the use of renewable energy is not only eco-friendly but also economic friendly as it eliminates risk involved with the fluctuating price of fossil fuels and fosters employment in renewable energy related sectors (Früh, 2013). Therefore, through decentralized energy generation, microgrids minimize energy loss during transmission as well as expand access to renewable energy for community consumers (Nahhas & Ibhadode, 2022). In the case of the UK, the use of microgrids could help execute demand side management measures that estimates energy usage on the basis of available supply, making the energy market a lot more balanced and sustainable.

1.2 Problem Statement

This paper reveals that the current United Kingdom energy market structure presents three interrelated challenges to the society's concerted efforts to achieve sustainable development objectives. First, there are challenges in the market integration of renewables, expanding from grid access issues to wholesale electricity markets which undervalue the benefits of the technologies in terms of policy support (Früh, 2013). Second, the current pricing strategies provide incentives for unsustainable behaviours at both the wholesale and retail levels while being detrimental for low-income consumers. Third – despite its inherent advantages demand-side response appears to be underexplored due to regulatory constraints, weak price signals and disjointed market access. These are not unique issues but part of a systemic issue that arises from a flawed market model. Specifically, they did so under massive assumptions about societal consumption as passive, centralized generation as efficient, and price as the only competitive factor – all of which are no longer sustainable in energy practice (Dubash, 2003). Therefore, the gradual approach to transition has resulted in non-integrated reforms, with interfering and sometimes even conflicting incentive structures fundamentally reducing transition effectiveness. Hence, when these issues have not been addressed holistically, the UK may fail to meet its decarbonization goals and may further deepen energy inequalities in addition to decreasing public support towards the energy transition.

1.3 Challenges in the UK Energy Market

According to Giacomo Di Foggia and Massimo Beccarello (2024), the challenges that shape the UK energy market indicate that the integration of renewable energy sources has not been without issues regarding structures and regulatory frameworks. Gowreesunker and Tassou (2016) outlined that the Economic models in the offer often focus on immediate financial gains rather than on the long-term approach to sustainability. This has resulted in price instability, low implementation of renewable energy sources and socioeconomic constraints in accessing the energy for sensitive groups. The strategic approach mapped out by Nahhas and Ibhadode (2022) notes that renewable energy has the potential to generate significant improvements in the state of the environment but has to be backed up by supportive policies and investment incentives that are sustainable rather than profit-oriented. Therefore, the current infrastructure of the UK needs upgrades for intermittent resources like renewable energy (Gov.Uk, 2024). To create a stable renewable energy market, it is crucial to enhance the existing grid and storage technologies as stated by Nahhas and Ibhadode (2022). The Hybrid renewable systems, as evident from the energy requirements foreseen for the United Kingdom, also demonstrate how both electrical and thermal needs can effectively be met through the use of integrated resources such as wind and solar energy

1.4 Research Aims and Objectives

The aim of this study is to propose reforms that align the UK energy market with sustainability goals, specifically focusing on integrating renewable energy sources, establishing fair pricing structures, and implementing demand-side response measures. The objectives of the study are as follows:

1. To analyze the current profit structures and market dynamics in the UK energy sector.
2. To evaluate the impact of renewable energy integration on market stability, consumer pricing, and carbon emissions.
3. To assess the effectiveness of demand-side response mechanisms in promoting energy efficiency.
4. To propose actionable recommendations that support the UK's transition to a low-carbon, sustainable energy market.

1.5 Research Questions

This research addresses four interconnected questions:

1. How can the UK electricity market be restructured to prioritize renewable generation while maintaining system stability and security of supply?
2. What pricing mechanisms would ensure fair consumer costs while supporting renewable investment and reflecting system conditions accurately?
3. How can demand-side response be effectively incentivized at both individual and industrial levels to optimize system flexibility and support renewable integration?

4. What regulatory frameworks and implementation approaches would best support an integrated approach to market reform that addresses all three challenges simultaneously?

1.6 Significance of the Study

This research contributes to both theoretical understanding and practical policy development in several significant ways. Theoretically, it advances the literature on energy transitions by developing an integrated analytical framework that bridges previously siloed domains of market design, social policy, and sustainability transitions (Hammond, 2000). By synthesizing insights from economic theories of market design with socio-technical transition perspectives, the research contributes to more nuanced understanding of how market reforms can navigate complex trade-offs between competing objectives (Liu et al., 2022). From a policy perspective, this research is particularly timely given the UK government's stated intention to pursue comprehensive market reform following the energy crisis. The integrated framework developed here provides policymakers with a coherent approach to addressing multiple challenges simultaneously, potentially improving the effectiveness of reform efforts (Miao et al., 2020). Therefore, by evaluating international experiences and adapting them to the UK context, this research offers practical lessons for implementation that could help avoid costly policy missteps.

Chapter 2:

Literature Review

2.1 Theoretical Framework

Newbery (2016) identifies a number of threads of thought that are central to the literature on the formation and structure of energy markets, where each theory offers a more detailed understanding of how such a market should be designed to achieve certain goals. Whereas neo-classical economic theories view efficiency prices resulting from competitive mechanisms (Newbery 2016), institutional economics focuses of governance structures and transactional costs in shaping markets (Geels, 2019). The more recent theories in evolutionary economics have helped to explain the nature of innovation and dependencies in energy systems. These economic perspectives are further complimented by socio-technical transition theories that consider energy systems as systems integrating technology, institution, and activity (Geels, 2019). The multi-level perspective is especially useful when it comes to explaining how niche innovations are capable of destabilizing a regime. Another theoretical lens is energy justice that analyses the market structures in terms of distribution, process, and identity in line with Jenkins et al (2016). These frameworks shed light on such questions as for whom, at whose expense, and in whose interests market architecture is designed – questions that may be overlooked in orthodox economic theory. These theoretical orientations described above, are integrated below to converge into the concept of markets that encompass economic coordination, socio-technical governance and political distribution.

2.2 Renewable Energy Technologies and Integration

The quest for a sustainable world against global climate change has led people to shift to renewable sources of energy. Integral to this process is the utilization of renewable energy sources such as wind, solar PV and bioenergy that could help to replace fossil fuel based electricity generation with sustainable electricity generation systems (Newbery, 2016). The main problem related to utilization of renewable energy, especially wind and solar energy is the intermittent nature of the sources. Panda et al. (2023) observed that solar power is only available during the day and its availability is affected by the current weather conditions, while wind power depends on the condition of the atmosphere. These fluctuations pose questions that should be addressed in order to provide stability in supply of electricity and management of available power on the grid. In this regard, the concept of Hybrid Renewable Energy Systems (HRES) has been established as the most appropriate one. Incorporation of various sources such as wind turbines, solar PV panels, and bioenergy generators can compensate for the variability of individual generators in HRES and improve the availability of energy. Wood and Dow (2011) looked at an HRES model that can be implemented at a domestic scale to serve a house in the United Kingdom with the use of wind power, photovoltaic panels and a biogas genset system incorporating batteries for energy storage. This work indicates that such configurations can support the power and heating demands without relying too much on fossil resources. In this regard, the hybrid approach tends to balance the fluctuations in output and energy infrastructure sustainability of the sectors. One of the key challenges of HRES, as with any renewable energy solution, is energy storage. If storage solutions are not available, this can cause inefficiencies in the system or stability issues in the grid. In his 2013 paper Früh (2013) specifically looked at energy storage for wind power in the UK where have proposed a rule of thumb that storage systems should have a capacity of 10 MWh per MW of wind power capacity. This level is capable of handling short term storage on the grid, which is usually below one week at a time making the grid a more flexible one (Wood & Dow, 2011). Additionally, Wood & Dow (2011) focused on the role of energy storage as not merely an accompanying requirement but as a critical pillar for increased RES uptake. According to Wood & Dow (2011), bioenergy, particularly in the form of anaerobic digestion (AD), offers a unique advantage among renewable technologies.

Compared with solar and wind power, which are dependent on environmental condition, AD has the potential of continuous and flexible power generation. The plant takes organic materials like agricultural waste or food scraps and digests them using microorganisms and then produces biogas, which makes it useful for areas that rely on farms or have a lot of agricultural activity. In their work, Gowreesunker and Tassou (2016) identified AD as a decentralised energy technology that is designed to both generate electricity and heat. This dual-output capacity means that AD is also useful and even valuable in providing an extra layer of local energy resilience (Dubash, 2003). In addition, because the feedstock for AD is waste material, and the end-product is a valuable fuel, it also leads to waste management and circular economy which further increases the sustainability of the process. Furthermore, bioenergy from AD can bring stability to HRES configurations when incorporated. Therefore, wind or solar power has fluctuations, with days that have high output and others with little to none, but dispatchable power complements the intermittent resources by providing a stable energy output. This factor is crucial in rural or off-grid conditions where grid connection may be unavailable or sporadic.

2.3 Cost-Effectiveness and Carbon Reduction of Renewables

According to Cabot and Villavicencio (2024), the introduction of renewable energy technologies into the energy supply system of the United Kingdom is spurred by factors other than environmental considerations but also the economics of the situation. Within these industries, it is becoming increasingly important to obtain cost-effective solutions to simultaneously reduce cost and carbon outputs for the sake of long-term viability and larger scale take up. An example of such a technology is the air-source heat pump (ASHP). According to Bettarelli et al. (2024), ASHPs appear to offer a convincing solution for the transition to low or zero carbon heating systems from the domestic sector, a contributor to a significant percentage of the UK's CO2 emissions. While ASHPs are more expensive in terms of capital investment when compared to conventional gas boilers, the cost of energy and the maintenance costs are higher in the long run (Bettarelli et al., 2024). These systems can give homeowners significant savings over their lifetime, when used alongside insulation, for example, or smart thermostats. Moreover, ASHPs are electrical heating systems and when coupled with renewable electricity sources, carbon emissions from space and water heating are virtually non-existent. This attribute is consistent with the United Kingdom's net-zero emissions plan that highlights electrification of heating systems as one of the key pathways of decarbonization.

However, government incentives, including in the form of subsidies like the Boiler Upgrade Scheme (BUS) in the UK that provides grants for ASHP deployment, significantly enhance cost viability and offer a means of market penetration. They assist in sharing the initial cost of investment so that more people can embrace low-carbon heating systems within their households. This means that as the grid increasingly transitions to clean energy, the carbon benefits of ASHPs will increase also, further solidifying the role of ASHPs as sustainable solutions for residential homes (Bettarelli et al., 2024). The application of AD has been found to be most beneficial to the agricultural community as an area of specialization in harnessing renewable energy. AD systems process primarily animal waste, agricultural and plant residues, and food waste into biogas, which can be utilized for electricity and heat or further refined to biomethane to inject into the natural gas grid (Jamal et al. 2023). Gowreesunker and Tassou (2016) discussed the benefits of AD, noting that, in addition to generating renewable energy, it also solves the problem of waste disposal. The inclusion of AD systems not only decreases the cost of waste disposal but also decreases the use of external energy inputs The feed-in tariffs (FiTs) and Renewable Heat Incentive (RHI) payments, and revenue generated from energy sales back to the grid can be earned.

From the carbon reduction standpoint, AD greatly reduces GHG emissions because it replaces fossil fuel energy and avoids methane emissions from organic waste decomposition. This is particularly important not only in terms of meeting the UK's carbon budgets but also in terms of improving the sustainability of the agricultural sector (Hammond, 2000). Additionally, the nutrient-rich solid by-product, digestate arising from AD process, can be utilized as an organic fertilizer thereby eliminating the use of synthetic materials in farming practices hence lowering their impact on the environment as well. In particular, both the ASHPs and AD systems highlight the relevance of policy support in enhancing the economic viability of renewable technologies (Liu et al., 2022). According to Poudineh et al. (2020), supports from the government in the form of subsidies, tax credits and financial assistance for research and development can help address the challenges of high initial capital investment and operating costs. Thus, as these technologies become more mainstream and enjoy increasing scale economies, the overall market appeal deepens and the extent of their contribution to the national decarbonisation agenda rises correspondingly.

2.4 Challenges in Renewable Energy Adoption and Market Reform

There are, however, several barriers facing the large-scale uptake and implementation of sustainable technologies in the United Kingdom despite the progress made and rising policy support. This is because these difficulties are manifold, entailing the economic aspects, infrastructure, and the legal frameworks. This knowledge is crucial for the formulation of strategies on how best to optimize the change towards a more climate friendly energy system (Warren, 2014). One of the most fundamental problems can be identified in the character of the UK energy market that is supply-side institutionalised and short-term value-driven (Warren, 2014). The issue with this market is that it discourages long-term investment in renewable systems that is long-term in nature and often demands significant up-front capital and payback time. LSEs can operate under normal market conditions pursuing financial profitability, which means that they can have an incentive to invest in a power plant that will be profitable in the short run but negatively impacts sustainable development in the long run, such as natural gas or Peaker plants. This short-term thinking hampers the continuity necessary to make under dispersed renewable technologies, and results in price fluctuation and investment risks, making it difficult for new entrants and investments in the renewable sector (Wood & Dow, 2011). Specifically, it is more challenging for first movers or smaller renewable energy developers as they struggle to secure financing because revenues are uncertain and markets are often relatively immature.

Beside market structure other challenge to renewable integration include inadequate infrastructures. Wind and solar are intermittent and variable sources whose fluctuating input requires a strong grid to accommodate and manage. Früh (2013) highlights the critical role of energy storage systems, particularly in the context of wind power. Lack of storage capacity means that energy produced during peak times cannot be stored thus resulting in energy wastage or curtailment. On the other hand, during low-output production, stored energy is not available and power backup often comes from fossil fuel power plants, which negates the benefits of renewable energy systems (Rhys, 2010). According to Rhys (2010), the UK's energy storage is not yet at a level that enables deep decarbonisation hence is displacing some operational issues and increasing supply-demand imbalance risks. Therefore, offshore wind farms and other renewable granting sites are frequently located in remote locations such as countryside or coastal areas, far from load centers (Rhys, 2010). This geographical mismatch places pressure on transmission capacity and requires the enhancement of the transmission network through reinforcement and the implementation of smart-grid technology. The time and money consumed with these enhancements critically hinder project development especially those fuelled and led by independent and communally-owned renewable projects. According to Miao et al. (2020), bioenergy technologies like the AD, however, come with their challenges. AD has the potential to reduce waste, decentralise energy generation, and result in carbon emittance reduction but UK take-up remains modest. Gowreesunker and Tassou (2016) outlined those objective challenges to AD deployment include high cost of capital, low return on investment, and regulatory issues. The cycles for planning and permitting can be extensive and complex and includes various agencies and environmental impact studies. Furthermore, the operation of AD systems relies on government subsidies or incentives that sometimes fluctuate or decrease. This is quite in contrast to nations like Germany where a stable policy environment that includes a feed-in tariff for renewable energy, assured grid connection, and a simplified approval process for the construction of AD plants has led to the growth of the AD industry and overall renewable energy sector (Miao et al., 2020). These figures underscore the relative weakness of UK policies and support systems, as well as the need for stronger, clearer instruments, targeted incentives and technical support for AD, and other forms of bioenergy.

2.5 Demand-Side Response

Rhys (2010) posited that while DSR moved in response to signals from the marketplace is beneficial in terms of balance, network and renewable resources integration. DSR is categorized into three types: event-driven DSR by the system events, price-triggered related to price signals, and time-of-use DSR based on direct load control (Poudineh et al., 2020). A plethora of opportunities remain untapped as evidenced by theoretical DSR capabilities explored in extant literature in various industries. Industrial and commercial consumers are preferred for large, well-defined, and concentrated load patterns that are suitable for frequency response and reserve services (Giacomo & Massimo, 2024). Goulden et al (2014) note that residential consumers have vast potential peaking flexibility via heating, cooling and EVs but are small overall (Goulden et al., 2014). Smart appliances, home energy management systems, and automation technologies are expanding the technical potential of residential DSR.

As highlighted by Rhys (2010), the current obstacles to DSR are Static product definitions anchored from generation characteristics, Minimum participation quantity constraints, Measurement and verification challenges, and the split incentive situation between bill payer and system operator. Hence, the development of aggregation models has emerged as a way of addressing some of the challenges brought by the distribution of resources through aggregation. This paper also finds that consumer engagement with DSR is not only driven by financial incentives. For instance, the literature has underlined automation in sustaining the engagement, with a view to understanding the influence of non-monetary motivations like environmental conservation, and trusting the providers.

2.6 Policy Implications

Policy Implications and Future Directions

According to Früh (2013), government policy is crucial in the advancement of renewable energy and in transforming the UK's energy mix and markets. While the target of achieving Net-Zero emissions is expected by 2050, it is crucial to address current challenges and coordinate policy frameworks for encouraging investment in green technologies and enabling the transformation of the economy. Of all the policy intervention areas, the biggest potential is in Residential sector where heating and energy consumption contribute to a large part of the national carbon footprint. Gowreesunker and Tassou (2016) outlined that scheme like the current Green Homes Grant and the upcoming Future Homes Standard launched by the UK government intentionally encourage the use of low-emissions technologies like ASHPs and wall insulation; since they provide subsidies to homeowners and developers which help reduce the costs associated with implementation and increase the pace of transition from conventional fossil-fuel based furnaces. Of specific concern is the Future Homes Standard which offers higher requirements for energy and carbon for new structures from 2025 onwards, making renewable technologies the new baseline for future housing. These policy measures do more than help to lower emissions; they drive the development of the green economy and demand skilled employees, supply chain services, and improved renewable technologies.

Cabot and Villavicencio (2024) outlined that, Anaerobic digestion (AD) has significant opportunities in the bioenergy context, but has not been widely implemented in the UK compared to the rest of Europe. Additionally, Gowreesunker and Tassou (2016) highlight Germany as another example of the successful implementation of AD systems due to positive direct policy support. The UK has faced issues with unequal incentives for renewable energy, slow planning processes and uncertain long-term vision in policies. More capital subsidies like capital grants, feed-in tariffs for green electricity or guaranteed access to the market for biogas producers could make AD financially viable and replicable more easily. Therefore, if properly funded, AD could produce a reliable dispatchable renewable power source that can work in tandem with intermittent technologies and also solve agricultural and food waste issues. Future energy policies must consider the structural trends within the current energy system, and the policies that have deterred extended pay-back renewable investments.

The pre-eminence of self-interest, transactional approaches—stressed by Poudineh et al. (2020) emphasised the need to reinvent market logics for better long course adaptability. This could be done through long-term power purchase agreements (PPAs) for renewables, carbon pricing, or through capacity markets that incentivize flexibility from low-carbon technologies. One promising area is the support for energy storage and DSR as they are necessary to deal with the variability and uncertainty of renewable generation and ensure the reliability of the grid. In this regard, Früh (2013) has called for increased policy support for storage systems including battery, pumped hydro, and thermal storage to enable some of the excess renewable power to be stored and used in periods of lower generation. Similarly, shifting demand, where consumers control their demand based on supply, can help achieve levelized demand, minimize load on the electricity network, and decrease system costs. The use of smart metering, time-of-use tariffs, and grid-interactive technologies will enable consumers to engage effectively in energy flexibility markets (Sovacool, 2017). Therefore, emphasis should be placed on integrating regional and community energy planning into the policy mix to foster local stewardship, reliability, and innovation. Community energy projects can help increase the acceptance of renewable energy and pave the way for more integrated restructuring of the energy sector when backed by adequate finances and favourable policies.

Chapter Three:

Methodology

3.1 Research Design

Based on such an understanding, this study is an exploratory mixed-methods study conducted to examine the United Kingdom’s progress toward smart, sustainable, inclusive, and resilient energy markets. Thus, for the technical and non-technical aspects of energy systems and their restructuring, the mixed-methods approach is more robust based on, the quantitative analysis and policy assessment as well as power system modeling (Sovacool, 2017). Measurable variables include availability of renewable energy, electricity costs, the viability of mixed electric systems, and CO2 emissions. These figures are important as they provide a baseline for the size of the market and the feasibility of introducing different forms of renewable energy to the grid (Sovacool, 2017). This will be particularly useful in adding to the quantitative portion of the analysis by providing an understanding of rules, policies, and consumer engagement activities relevant to the actual reform processes. This includes the evaluation of the most recent policy frameworks, industry literature, and the systematic analysis of UK energy programmes. Together, these components are intended to form the foundation of an actionable model that policymakers and stakeholders can use to assess and coordinate market reforms using perspectives grounded in continual improvement, affordability and demand side engagement.

3.2 Data Collection Methods

3.2.1 Quantitative Data Collection

In an effort to analyze the UK's progress towards established goals and objectives, quantitative data collection involves collecting numerical information on energy usage, renewable energy production, energy tariffs and carbon footprint (Panda et al., 2023). Such data are crucial for understanding the feasibility of the shift to a low-carbon energy system in both technical and economic terms.

Some of the most common quantitative data sources are:

- ***UK government***: These sources provide official energy statistics from the UK DESNZ and ONS.
- ***Ofgem documents***: This offers regulatory information regarding the trends of retail and wholesale prices and the protective measures that are implemented to safeguard consumers.
- ***National Grid Reports***: Daily, and actual metered electricity consumption, renewable generation, and system balancing information is gathered.
- ***Climate Change Committee Publications***: Benchmark reports and carbon budget assessments shed light on the current trend towards achieving net zero.

The study specifically analyzes:

Historical and current electricity prices to examine the variation in price trends, evaluate the rate of consumer affordability, and the impact of price control mechanisms such as price caps. Sources of energy such as carbon emissions from coal, natural gas, wind, and solar as well as bioenergy for the assessment of environmental impact (López González &

Garcia Rendon, 2022). Renewables generation stats to monitor the growth in wind, solar, hydropower, and bioenergy installed capacity and usage percentages. Furthermore, based on modeling parameters derived from Miao et al. (2020), the study analyses the viability of hybrid renewable energy systems (HRES). These parameters include: Net Present Cost (NPC) which refers to the cost of implementing and maintaining HRES over the entire lifecycle period. Levelized cost of energy (LCOE) which is the cumulative amount of money required to build the infrastructure for generating a unit of electricity, operation expenses together with the cost of maintenance over the lifetime of a power plant (Newbery, 2016); and renewable penetration rates which helps understand how different levels of renewable energies impact the stability and economics of the grid.

3.2.2 Qualitative Data Collection

To complement the quantitative analysis, the qualitative data allows a better assessment of the institutional, regulatory, and behavioral aspects of energy transition. Based on a large number of documentary sources, the paper aims to assess how policies, incentives, and stakeholders' perceptions impact the evolution of markets.

Primary qualitative sources include:

- ***Government documents***: For instance, the UK's Net Zero Strategy, Energy White Papers, and guides on the new Green Homes Grant. These papers shed light on the plans and potential measures on the path to decarbonisation and reasonable energy tariffs.
- ***Industry Reports***: Published by organizations such as the Energy Systems Catapult, Carbon Trust, and the Renewable Energy Association. These reports can offer insights into the adoption levels, gaps in technology and infrastructures as well as the overall state of preparedness in the market.

- ***Scrutinizing of case studies***: This study draws on studies from Früh (2013) who establishes the role of financial incentive and energy storage in renewable integration.

As noted by Liu et al. (2022), qualitative strategies measures such as Green Home Grants motivate homeowners to adopt energy-efficiency improvements or use distributed renewables, alleviating load burden and engaging demand-side management. Therefore, the integration of renewable energy sources like lithium-ion batteries and pumped hydro storage to maintain reliability in supply is crucial to curb the instabilities that stem from renewable resources as noted by Früh (2013). These are then systematically integrated and analyzed, to determine whether contemporary UK policies are sufficiently enabling consumer engagement particularly concerning DSR initiatives. Therefore, examining case studies on best and engaging DSR programs, this study discovers best practices and challenges that may hinder the expansion of these solutions across the country.

3.4 Modelling Techniques

As highlighted in figure 1, to evaluate the diverse and complex implications of integrating renewable energy, adopting fair price mechanisms, and increasing the demand side flexibility in the UK electricity market, this analysis utilises a range of integrated and comprehensive modelling tools (Cabot & Villavicencio, 2024). These are important in capturing the impacts of various reforms on cost of the system, security of supply, carbon intensity and consumer participation. The models act as both diagnostics and forecasting mechanisms, thereby providing the basis for policy making that is grounded in real and computer-generated data (Cabot & Villavicencio, 2024). In detail, as highlighted in figure 1, the HRES modelling is employed by integrating HOMER software and a scenario-based approach is used to assess the potential impact of particular market reform measures under varying regulatory pathways.

According to Wood and Dow (2011), hybrid renewable energy systems (HRES) modelling is another important area of research in the new energy landscape with much attention paid to how different systems work together to provide efficient energy supplies. One of the building blocks of this study is the simulation of Hybrid Renewable Energy Systems (HRES) with the help of the HOMER™ software package. HOMER, an industrial-grade tool that has been used to select microgrid systems in terms of different renewable resources to store and backup sources, is frequently employed to evaluate the techno-economic feasibility of decentralized systems, especially the integration of solar PV, wind, and bioenergy with battery storage (López González & Garcia Rendon, 2022).

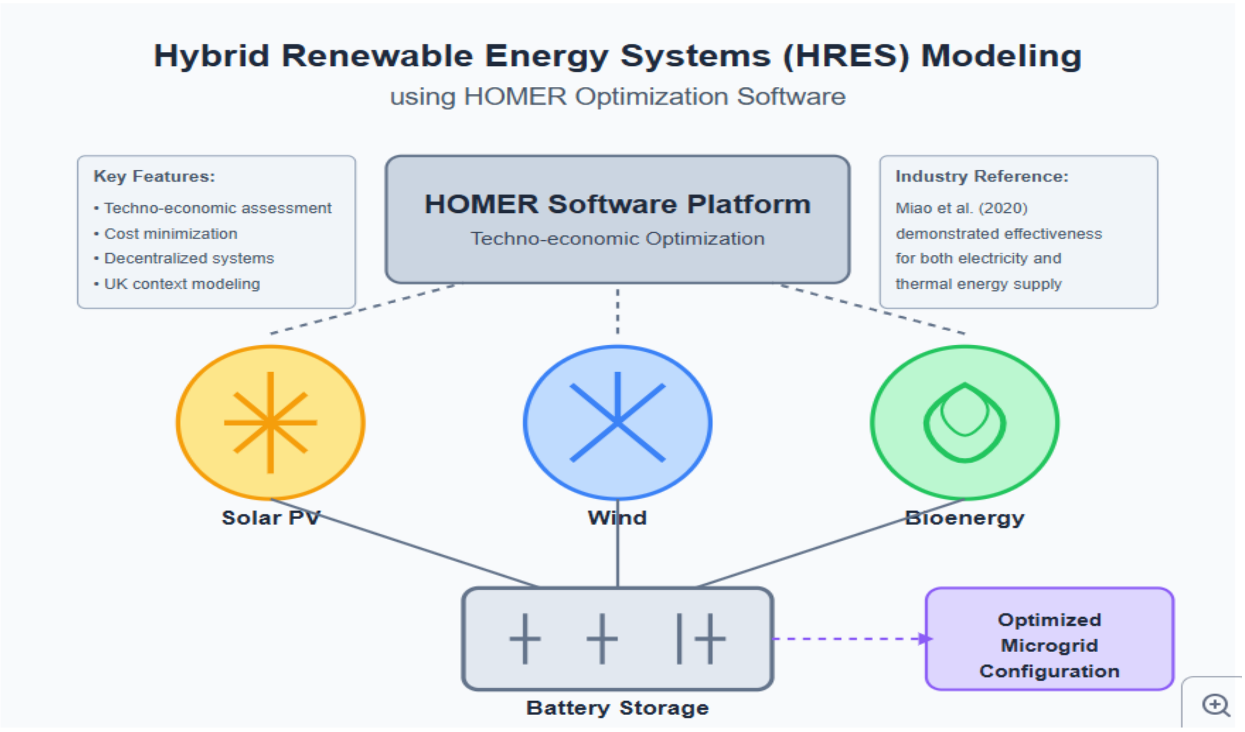

Figure 1: Hybrid Renewable Energy Systems (HRES) Modelling

3.4.1 Model Configuration

As highlighted by Giacomo Di Foggia and Massimo Beccarello (2024), the HRES models used in this research are therefore designed to accurately reflect the conditions of the UK energy sector – at least to the highest degree possible. , as shown in figure 2, includes a key set of renewable technologies, namely solar PV, onshore wind, and bioenergy from AD. Energy storage solutions are deployed alongside battery storage technologies to ensure system reliability and energy availability during periods of low renewable generation. So far as the storage part of the model is concerned, Früh (2013) argued that there must be at least 10 MWh storage capacity available for every MW of wind energy capacity. This ratio is strategic because it can help adjust for temporal disparities in needs or availability such as seasonality (Panda et al., 2023). The storage component is expected to help levelize the load curves over short time horizons and supplement low generation over longer periods. Load profiles are further classified into two types, residential class load profiles and community class load profiles. There are household models where the appliances and equipment are characteristic of an average household in the UK, and community models which represent the energy consumption of towns or collective living (Panda et al., 2023). These profiles are then further calibrated by including measures related to energy efficiency and electrification, including factors like heat pumps and electric vehicles.

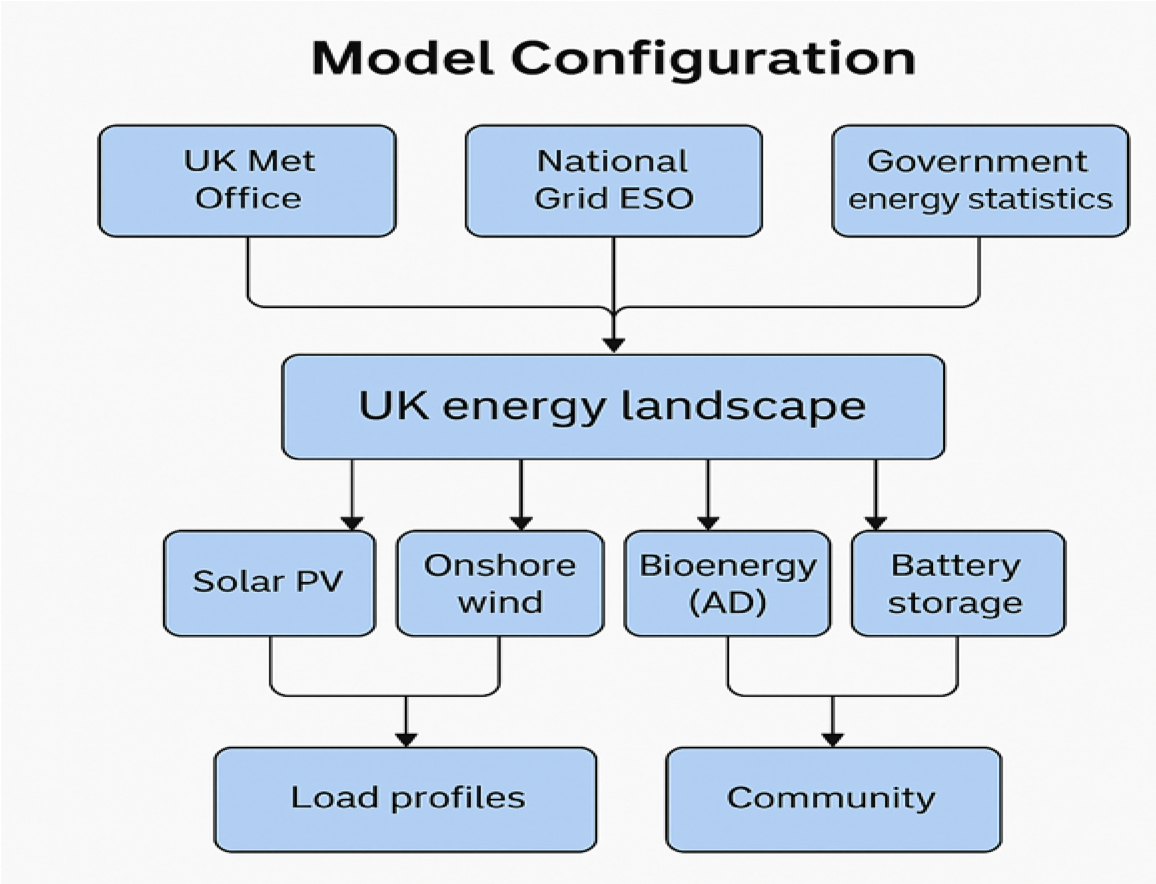

Figure 2; Model Configuration

3.4.2 Cost-Effectiveness and Carbon Reduction Analysis

Wood and Dow (2011) identified that there are two basic aspects of techno-economic assessment: Levelized Cost of Energy (LCOE) and Net Present Cost (NPC). LCOE reflects the lifetime cost per kilowatt-hour of electricity generated by the system, based on installation, running, repairs, and replacement costs (Panda et al., 2023). Sovacool (2017) stated that NPC includes the total cost of the whole system throughout its life cycle, which allows for the long-term economic comparison of various configurations. Simulation results are discussed in light of conclusions drawn from Wood and Dow (2011) where they posit that long-term costs of RE and overall carbon emission might be reduced whenever there is proper alignment of policy support structures as proposed by Sovacool (2017). The optimization results from HOMER reveal that selected HRES configurations, especially the solar-bioenergy integrated systems properly equipped with storage systems, can provide LCOEs below the UK average retail price for electricity of about £0.30/kWh, hence, making HRES economically feasible. However, there are significant reductions in emissions, with estimates of CO_2 emissions being 80% lower than grid electricity derived from natural gas (Wood & Dow, 2011). These findings underpin the applicability of HRES as a foundation for decentralised, sustainable energy projects in the UK, and suggest the possibility of energy and carbon autonomy within local communities.

3.4.3 Scenario Analysis for Energy Market Reform

Fundamentally, scenario analysis is a strategic tool utilized for assessing the effectiveness of energy market reform structures based on their sustainability, price-oriented fairness, and consumers' shields (Bettarelli et al., 2024). This analytical framework can be utilized to look for issues, opportunities, and trade-offs for various pathways for market transformation. For comparison purposes, three different scenarios have been developed: the Baseline Scenario, the Renewable Incentivisation Scenario and the Demand Side Response (DSR) Scenario. They describe different paths of evolution for the future of the UK energy market and their implications for the key reform goals.

3.4.3.1. Baseline Scenario: Status Quo Market Structure

According to Dubash (2003), the Baseline Scenario describes the current state of the British energy landscape where the major principal energy companies control the five major types of infrastructure but operate in a market where competition is allowed though structured in a monetised framework. In this model, market dynamics persist to align more with short-term financial profit, at the detriment of long-term environmental preservation and reasonable consumer prices as outlined in table 1. This scenario reveals several critical shortcomings of the conventional energy market structure which include;

Limited Renewable Integration: While countries have pledged to reduce emissions and move towards green energy, the current legislation does not offer enough incentives or infrastructure to support the widespread use of renewable energy sources.

Fluctuating Prices: Self-regulating fossil fuel markets on the global front instigate fuel poverty amongst the vulnerable populace, especially the low-income bracket.

Consumer Disempowerment: Consumers are confined to passive roles where they are unable to control their energy consumption or the sources of supply in their own homes.

Therefore, in this scenario, we have a benchmark to consider when assessing the need and viability of reform (table 1).

3.4.3.2. Renewable Incentivisation Scenario

As outlined in table 1, this scenario considers a shift in the market structure towards increased penetration of RE technologies through improved policy measures. Building on the policy recommendations forwarded by Gowreesunker and Tassou (2016), the model evaluates the likely effects of increasing different forms of financial incentives such as the Feed-in Tariff (FiT) and the Renewable Heat Incentive (RHI), aptly developed for the expansion of decentralised renewable generation.

These key characteristics include:

Improved Subsidies and Tax Credits: New knowledge support structures are proposed to boost the implementation of the current and new technologies like the anaerobic digestion (AD), the solar photovoltaic (PV), and renewable hybrid power systems comprising of the solar power, wind and battery storage.

Micro-generation: Residential users, farmers and communities are encouraged to act as prosumers by generating their own power and feeding it into local networks.

: Technical implications – use of cleaner sources of energy that will lower greenhouse gases as the economy transitions away from fossil fuel.

Career Opportunities: Rural areas also experience employment creation through enhancements in installation of renewable energy sources and their maintenance.

As outlined in table 1, the scenario assesses the viability of subsidised renewables in the long run, as well as pragmatic barriers for administration and financing of these schemes. It also looks at issues like over-subsidisation and measures that should be put in place so that cost recovery can be extended fairly across the consumers.

3.4.3.3. Demand-Side Response (DSR) Scenario

DSR Scenario is a future state in which the energy market has transitioned to a demand side management market where the full dynamic of consumer energy is taken into account. This is based on the study by Bettarelli et al. (2024) who have embraced flexible and decentralised energy networks, time of use tariffs, community microgrids, and real-time management systems.

Key elements of the DSR Scenario are the following:

TOU Rates: Consumers are charged differently depending on the time of day, forcing them to use energy during other times of the day instead of during peak hours, improving efficiency of the system and its generation during peak hours.

Smart Meters: Large-scale implementation of smart metering enables consumers to collect detailed meter data, helping them better manage energy use.

Community Microgrids: This covers localized systems for sharing electricity and or providing emergency power through the use of microgrids, common in rural or low density areas.

Behavioural Changes: Price signals affect consumer behaviour, leading to more variable demand and reduced dependence on centralized fossil fuel power plants.

This scenario examines the role of real-time pricing and dispersed energy storage for system reliability and its cost implications (Bettarelli et al., 2024). It also reviews equity implications—specifically, demand bill burden shifting to lower income consumers who may be unable to manage their consumption to accommodate ToU rates with appropriate sensitization (Table 1).

Table 1: Comparative Evaluation

Each scenario presents distinct outcomes and trade-offs, which are summarised in the table below:

Scenario	Sustainability Impact	Consumer Cost Implications	Market Resilience	Equity and Fairness