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A Qualitative Based Causal-Loop Diagram for Understanding Policy Design Challenges for a Sustainable Transition Pathway: The Case of Tees Valley Region, UK

Bjarnhedinn Gudlaugsson [1,*], Dana Abi Ghanem [2], Huda Dawood [1], Gobind Pillai [1] and Michael Short [1]

[1] Centre for Sustainable Engineering, School of Computing, Engineering and Digital Technologies, Teesside University, Middlesbrough TS1 3BA, UK; h.dawood@tees.ac.uk (H.D.); g.g.pillai@tees.ac.uk (G.P.); m.short@tees.ac.uk (M.S.)

[2] School of Social Sciences, Humanities and Law, Teesside University, Middlesborough, Tees Valley TS1 3BX, UK; d.abighanem@tees.ac.uk

* Correspondence: b.gudlaugsson@tees.ac.uk

Abstract: The energy transition is a complex problem that requires a comprehensive and structured approach to policymaking. Such an approach is needed to ensure that transition pathways and policies enable greener energy alternatives whilst ensuring prosperity for people living in the region and limiting environmental degradation to the local ecosystem. This paper applies a qualitative approach based on systematic literature research and review analysis to identify and analyse previous work within this interdisciplinary field in order to understand the complexity of energy transitions and identify key variables and sub-sectors that need to be addressed by policymaking. The paper then looks at the problem from a regional level and uses the Tees Valley region in North East England as a reference case for the energy system and potential proposed policies for the energy transition. A system dynamics methodology was employed to help visualise and emphasise the major complexity of the energy transition and the challenges that policymaking needs to tackle for the successfully enable implementation and application of the energy transition policies. The results of this study identified that in relation to the Tees Valley energy system, its development and transition towards decarbonisation, the major challenge for the policymakers is to ensure that proposed policies foster growth in job creation without leading to job losses within the local employment market.

Keywords: system dynamics; energy transition; energy systems; policy-design; causal loop diagram; extensive structure literature review; United Kingdom

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1. Introduction

The utilisation of fossil fuel energy resources has been one of the key drivers of societal growth for centuries, and since the industrial revolution, energy systems have been increasingly conceived on the burning and extraction of fossil fuel resources: referred to today as the conventional energy system [1,2]. However, it has been known since the 1980s that the utilisation and dependency on fossil fuel resources are unsustainable due to two principal factors: (i) the environmental degradation and climate instability caused by the extraction, production, and burning of fossil fuels, and (ii) the exhaustibility characteristics of fossil fuel resources is forecasted to lead to resource scarcity in the coming decades [3]. This knowledge of the negative characteristics of conventional energy systems affirms that the current global energy system cannot be considered sustainable for current or future generations and, indeed, is causing economic, societal, and environmental damage [1,3–6]. This has been made even more evident in recent years with the world facing various energy-related threats and growing impacts of climate change caused by burning fossil fuels, which has resulted in increasingly extreme weather phenomena, depletion of natural resources, and environmental degradation [2,5,7–11]. These threats pose a pressing demand on the global society, and policymakers at all levels need to deliver policies that push for the development and transition of energy systems towards renewable energy technology (RET), decarbonisation, and smart energy consumption [12,13]. Through policies that foster innovation and research into new and current energy technologies, investment into RET, infrastructure upgrade and adaptation, retrofitting buildings, and improving buildings standards to decrease energy demand alongside fostering social changes and acceptance, the sustainable energy transition that is needed can be enabled [8,13–15]. The United Nations Intergovernmental Panel on Climate Change (IPCC) highlighted this point by making the need for and importance of the energy transition and decarbonisation one of the focal points in their 6th assessment report published in 2021. The report stated that global society needs to see a rapid decrease in GHG emissions before the year 2030 to mitigate and avoid severe climate breakdowns expected globally by the end of the 21st century [11].

Over the recent decades, the transition toward a low carbon energy system has become an increasingly significant and important element in global and national policy and decision making [5,11,13,16,17]. This necessary restructuring of the energy system (and associated socio-economic impacts, e.g., traditional energy market disruption) is imperative to avoid climate breakdowns, prevent loss of environmental ecosystems and enable secure, stable societal growth through localized production of clean and affordable energy [5,8,11,14,15,18–20]. However, the energy transition is a highly complex and enormous task since, currently, close to 80% of the global energy comes from fossil fuels-based energy systems, and close to 75% of global GHG emissions come from energy system-related activities [2,11,13,17,21,22]. Furthermore, the tasks of the energy transition are multi-dimensional and require long-term economic planning involving both public and private investments into RET to enable technological innovation and adaptability, alongside the build-up of technological know-how and social aspects such as public and political acceptances [5,13,16–20]. Lastly, it needs governmental policies and strategies that are derived based on a clear understanding of the multi-dimensional complexity of energy transition which does not threaten energy security and geopolitical stability (through the planned or unplanned shifting of power and capital away from owners of fossil fuel resources), whilst enabling mitigation of climate change, ecological degradation, and social inequality [5,13,14,17,20]. Clearly, given the complexities and impact potential of energy transition choices, the deployment of methodologies and tools for the accurate forecasting of the impact potential of complex decisions and their outcomes on multiple stakeholder groups would seem not only beneficial but mandatory.

This study focuses on the case of the Tees Valley region in North East England and considers the energy transition policy plans that the United Kingdom (UK) government has set forward to meet its tasks of net-zero by 2050 [23–27]. These plans focus on improving the energy production capacity of renewable and low carbon energy technologies already in the energy mix, alongside introducing hydrogen production and energy storage technologies. It also includes energy efficiency improvements for space and water heating, through the introduction of a central heat network and heat pumps, alongside increasing the standards for building insulation in an effort to decrease the energy demand [13,17,23–29]. The objective of the UK energy transition and climate change mitigation plan is to achieve close to a net-zero emission target by 2050, in comparison to the 1990 levels [23–29] and at the same time foster positive job growth [23–26,29]. Furthermore, the Tees Valley region is considered a highly deprived area, and it has recently been ranked one of the top 10 deprived areas in the UK, alongside being an area with a high volume of energy-intensive industrial activities, and most of the energy produced in the region comes from nuclear energy [30–33]. In addition, in recent years, the region has seen a large industrial complex in the region close down, which has led to a rapid decrease in CO_2 emission, alongside bringing a socio-economic impact in the area with loss and lack of job opportunities [30–33]. This is partly due to the ongoing regeneration in industrial activities following the post-industrial decline of the area and an ongoing focus upon (i) decreasing CO_2 emission for an existing industrial complex and (ii) generation of new, zero-carbon industries to support national net-zero and green economy efforts [30–33]. The UK governmental plan, therefore, plays a big role in Tees Valley's energy planning, and in turn, the region is involved in several flagship policies that are critical to wider new zero efforts: the focus of these regional policies and incentives include the introduction of new hydrogen technologies and the buildup of significant wind energy production capacity [30–33].

As highlighted earlier, energy transition policymaking is a complex and multifaceted problem involving a large number of stakeholders, requires long-term planning and investments, as well as overcoming the structural internal and external dependency of energy systems [1,2,5,13,16–20]. This often leaves the process of policymaking being performed under a degree of uncertainty, due to the multi-dimensional nature of the problem, with various changeable objectives and goals depending on the geographical location and international commitments [1,2,5,11,13,15–20,22]. Furthermore, it involves a larger volume of variables, which are interlinked and crossover the economic, societal, environmental, and technological dimensions of society [12,34–37]. Therefore, it is highly important to apply a tool that allows for the capturing of these dynamic relationships. System dynamics is often seen as a highly effective methodology to capture such dynamic relationships. It offers a way to construct a qualitative illustration of dynamic relationships through the application of causal loop diagrams [38–45]. The reason for selecting and applying this method is reinforced by the fact that, in recent years, the system dynamics were applied to problems related to analysing and assessing energy transition and energy planning, such as alternative fuel vehicle implementation and integration policies [46–48], implementation and impact of biomass energy [34,49,50] planning of residential buildings' energy use in smart cities [51–53], country-level evaluation of renewable electricity development, understanding urban sustainability on a city level, and understanding sustainability and the social aspects of energy systems [54–57]. These applications make system dynamics modelling ideal in the case of Tees Valley because it illustrates the complexity the Tees Valley policymakers are facing when deciding on energy transition and energy system development policy in the area. Besides, capturing the interrelationship between the society, economy, and environment concerning energy transition and energy system development allows for looking at the impacts of those policies across those three dimensions, thereby enhancing the understanding of the policies and improving their successful implementation.

Topics such as the energy system, sustainable energy transition, renewable energies, sustainable energy development, energy modelling, decision making, urban energy planning, and indicators that are relevant to the convoluted challenges the global society is facing when it comes to energy transition have been highly researched and reviewed in recent years.

Nevertheless, from reviewing the literature, it was evident that limited research was conducted looking at specific regions within the UK, more specifically small regions within North East England such as the Tees Valley Region. The attention to energy transition policymaking and climate mitigation is based on a national-level viewpoint. National level sustainable energy transition plans are often aspirational as it is highly important to understand that their real-world impact is based on local governments translating them into policies and actions which are meaningful for the region. Therefore, to address this knowledge gap, this study draws on the Tees Valley region and focuses on presenting the first step in the development of a system dynamic model, which was applied to assess energy transition policies and their impact in relation to the three spheres of sustainability. The study covers the following steps of the system dynamic model development process: (a) problem identification and conceptualisation; (b) system conceptualisation, which involves identification of the dynamic modelling hypothesis, identification of the systems modelling variables, and illustrating the dynamic relationships and feedback loops within the system. In order to ensure the successful construction of a qualitative causal loop diagram of the energy system, which represents Tees Valley, it was crucial to capture the relevant modelling variables alongside identifying and understanding the dynamic relationships between energy transition and energy system development. An extensive structure literature review approach was used as the main data collection approach for this study. This approach offers a comprehensive and systematic process to identify and select relevant papers for review and data collection. In recent years, a systematic review has become common practice within research fields that fall broadly under sustainability and energy transition [58–62].

This research intends to contribute insights that can enhance the understanding of Tees Valley's energy system in relation to localised energy transition and system development. Furthermore, no research was previously carried out that focuses on mapping and illustrating the dynamic relationships and complexity of energy transition and energy system development in the context of the Tees Valley's energy system from a localised viewpoint. The objectives of this paper are to:

1. Capture and illustrate the complex situations policymakers are facing when it comes to the design and development of energy transition and energy system development policies;
2. Present a qualitative system dynamic model that visually illustrates and captures the complexity policymakers within the Tees Valley Combined Authorities are faced with when it comes to the region's energy system development and energy policies;
3. Identify and illustrate the main feedback relationships within the system and highlight the internal challenges;
4. Provide the groundwork for the development of a dynamic modelling assessment framework based on the integration of system dynamics and sustainability assessment to enhance the robustness and comprehensiveness of Tees Valley Combined Authority's energy policy assessments.

The paper is structured as follows: Section 1 provides a brief background literature review on the terms "Energy System", "Energy System Modelling", and "Energy Transition Policies", a review and insight into the UK energy transition policies and the complex landscape of today's energy transition policymaking. Section 2 explains the methodology and describes the main steps of the research process carried out during this study. Alongside providing brief background information on Tees Valley and the characteristics of its energy system, Section 3 presents the paper's main findings, focusing on the synthesis of results from the literature review into a conceptualisation model of the complexity of the energy transition and presents the causal loop diagram, which represents the qualitative system dynamic model for the Tees Valley region. Section 4 discusses the limitations of this study as well as future work planned, and Section 5 offers conclusions, highlighting the complexity of energy transition and the major internal challenges Tees Valley's policymakers face when it comes to a policy designed in relation to the energy transition in the region.

2. Background

2.1. Energy System

As energy is a crucial resource and factor in any development from the global level to the urban level, it is vital that it successfully delivers stable, affordable, and clean energy to its end users [1,14]. The key functions of an energy system are to acquire energy resources such as raw fuels such as oil or natural gas or harness renewable energy resources (RES) such as solar and wind to produce and successfully deliver electricity and district heating successfully to their end-users. Energy plays a vital role in life satisfaction and stability in people's lives as they depend on it to carry out many key tasks, whether it is the production and delivery of goods and services, providing healthcare, or storing of food at both commercial and household level [63]. The complex role and structure of an energy system are framed within the supply and demand principles, and the system's focus is on the acquisition of resources that are required to produce the energy needed to meet the demand of the end-users as well its delivery and finally understanding the end-users' consumption patterns [1,4,21,63–66]. Figure 1 below illustrates the energy system via four main building blocks of an energy system and four implementation supporting activities across the national, regional, and urban levels.

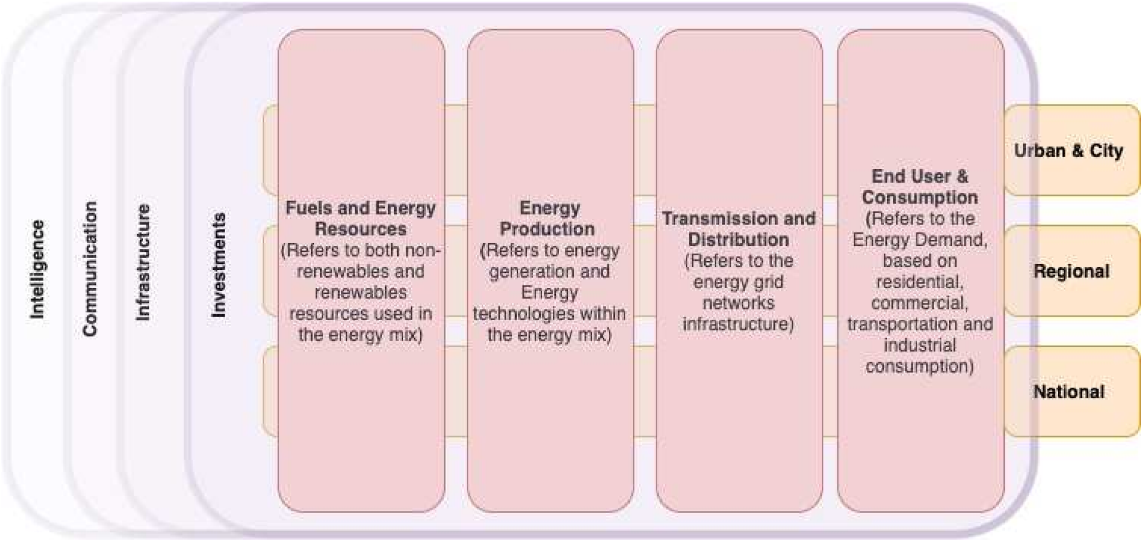

Figure 1. Energy System with its four main buildings block and four implementation supporting activities.

Furthermore, Figure 1 highlights that an energy system is complex and requires good integration and synergy between different buildings blocks and implementation activities to deliver its role within modern society successfully [1,16,63,67,68].

Despite this complexity, it is crucial for future generations and the Earth's climate that current energy systems evolve and transition towards a cleaner and fully decarbonised energy system [11,16,19,20]. Given the aims of the study, the working definition of the term "energy system" focuses on the regional and urban aspects of an energy system within the context of the Tees Valley Region in North East England. Thus, in this study, the term energy system is defined as: a complex process value chain system constructed on the principles of supply and demand, which provides adequate and stable energy services through the production and distributions of energy to satisfy the energy demand of a diverse group local consumers within a given area.

2.2. Energy System Modelling

In recent decades, policy and scenario-based analyses were carried out by using energy system models. These models have become a prominent tool to help policy and decision-makers to understand and investigate the potential positive and/or negative impacts and behaviours caused by the implementation of various policy instruments. Most often, the investigated policies were intended to enable and contribute to the transformation of national, regional, and local energy systems away from conventional, highly fossil fuel-based energy systems towards a decarbonised and clean energy system [5,68–71]. Energy system models are used to analyse and understand different aspects, impacts, uncertainties, and behaviours related to the required transformation needed to achieve both global and national goals set forward by international agreements such as the Paris agreement in 2015 [71,72], and energy models have become an important tool to support and evaluate energy transition and planning [73].

Energy system modelling is often used to describe an energy system on a national or regional level and is therefore often highly complex [71]. Besides, energy system models often require a large volume of historical data on several variables when investigating scenarios concerning (i) the socio-technical and socio-economic aspects and impacts related to energy system transformation, (ii) technological development and change associated with the decarbonisation of energy systems, and (iii) energy transition towards climate mitigation targets [72]. Reference [74] highlighted the importance of energy models and their application when describing the main objectives of using energy system models to (i) understand and forecast future energy behaviour in relation to supply and demand,

(ii) evaluate the impacts of different policy instruments on the energy system based on scenario analysis, (iii) quantify the impacts of different policy targets on the energy systems, (iv) compare economic costs of different technology or policy implementation, and (v) provide support to decision and policymakers. Reference [73] confirmed and supported this by discussing that energy system modelling was used to evaluate different energy scenarios focusing on technology change rate and substitution mechanisms. Reference [19] additionally pointed out that energy system models can be used for various purposes, such as forecasting, optimisation and simulation, and analysing different energy scenarios.

This study takes on a top-down approach to present an integrated energy system model of the Tees Valley region energy system based on qualitative literature analysis. The model highlights the complex nature of energy transition and provides the groundwork for developing a computerised simulation model that can be used to support policymakers when it comes to energy transition on regional and urban energy system levels.

2.3. Energy Transition Policies and Their Challenges

The term energy transition refers to the transition from one type of energy or fuel source to produce energy, whether it is being performed on a global, national, or regional level [1,75,76]. Importantly, this should not cause a decrease in the transmission and distribution capability of the energy system during the transition and causes problems for end-users [1,13,41,50,75,77]. Ensuring that current and future energy transition policies are well designed, defined, and have achievable goals is paramount to the global society to help mitigate the impacts and damages caused by climate crises and environmental degradation linked to the burning or production of conventional fossil fuels [2,5,7–11,13,17,78].

Besides, there is also the prospect of conventional fossil fuel resource scarcity caused by the current rate of exploration of known recoverable energy reserves [11,37,79,80]. These key issues provide two key fundamental reasons why the global energy system needs to transition towards cleaner energy technologies. This needs to be led by policies that enable this energy transition both technologically and economically [13,17]. In recent years, energy transition policymaking has moved towards considering the broader perspective and complexity of the global society and interlinkages between human, economic, and environmental systems [77], as illustrated in Figure 2.

This shift in thinking and approach to energy policy and strategy design have led to current and future energy transition policies being designed with a high emphasis on providing stable, clean, and affordable energy services to sufficiently meet the energy demand in correspondence with societal and economic development needs [81], which embodies the core message of sustainability or sustainable energy development thinking. This puts the three dimensions of sustainability, environment, social, and economy, at the centre of the energy transition policies at any level [77,82]. This can be seen within the United Nations Sustainable Development Goals (UN SDGs) set forward in 2015 [83], where UN SDG 7 focuses on bringing affordable, reliable, and clean energy to all; UN SDG 11 focuses on making cities and human settlements more sustainable; and UN SDG 13 focuses on actions to mitigate and combat the impact of climate change on the global society [6,78,83,84]. This shift is in policy focus is also evident across the global society, with the United States, China, and European Union pushing forward strategies to become carbon neutral in the next three to four decades through energy transition towards a greener, more resilient, and carbon-neutral energy system, while ensuring societal growth and economic prosperity through increase job creation, stable energy supply, and affordable energy to all, alongside causing a low environmental impact on the natural ecosystem from the energy transition [82,84–86].

The UK's plans for energy transition and a greener society also adopt a comprehensive view with the objective of achieving a greener and sustainable energy system while at the same time bringing societal and economic prosperity to the UK's society [23–29]. The UK's main objectives are to decrease its GHG by more than 78% by 2050 based on 1990 levels and generate approximately 250,000 jobs in the UK [23–28]. Table 1 below summarises policy areas, policy impacts, and potential benefits. The mitigation of GHG emissions focuses on advancing offshore wind energy and low carbon hydrogen within the energy system alongside delivering new and advanced nuclear power stations [23–26]. In addition, it aims to foster faster growth and integration of alternative fuel vehicles into the transportation system and promote more cycling, walking, and use of public transportation among populations [23–25,27]. Furthermore, it includes investing in research and development into alternative and low emission fuels for ships and jets, building greener infrastructure and buildings, investing in carbon capture and storage technologies [23–29]. Lastly, the plan also focuses on combating biodiversity loss alongside restoration and protection of natural ecosystems through the protection of the natural environment, restoring natural habitats for wildlife, and making the needed adaptions in response to the impact of climate change on the natural environment and communities [23–29].

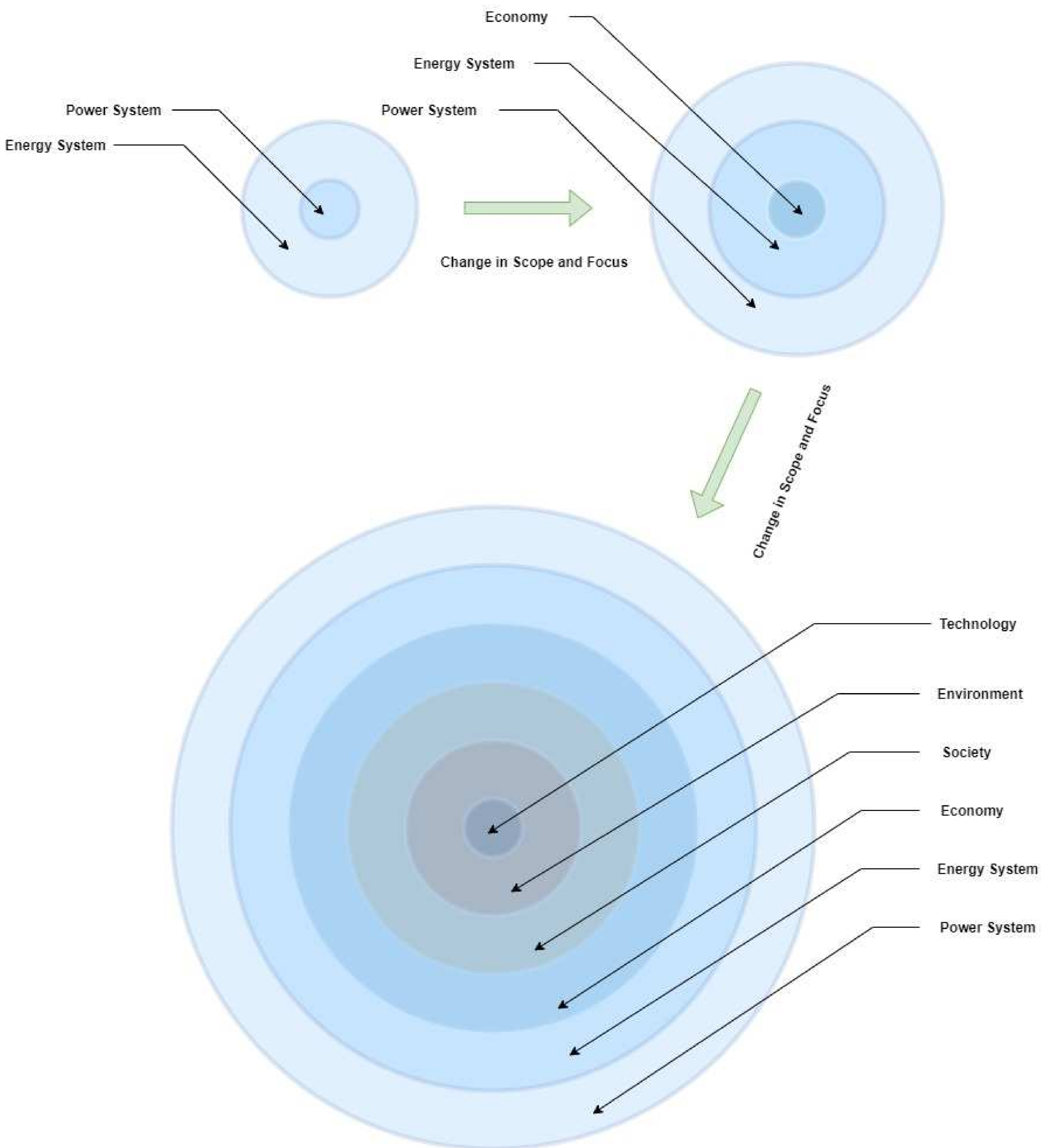

Figure 2. Energy Transition Policy Approach with embedded Sustainable Energy Development Thinking (Adopted from [77] p. 6).

Table 1. Key Areas, Impacts and Benefits from the United Kingdom Energy Transition Policies (Derived from [23–26]).

Policy Area	Policy Impact	Potential Benefits Delivered
Advancing Offshore Wind	Commitment to a 40 GW offshore wind target could help bring forth around GBP 20 billion of private investment in renewable energy. Coordinated offshore wind connections could deliver up to GBP 6 billion in consumer savings by 2050, significantly reducing environmental and social impacts on coastal communities. An estimated 60% of spending on UK offshore wind will be invested back into the economy by 2030.	Support for up to 60,000 jobs in 2030 around GBP 20 billion of private investment by 2030. Savings of 21 $MtCO_2e$ between 2023 and 2032, or 5% of 2018 UK emissions.
Driving the growth of low carbon hydrogen	Aiming for 5GW hydrogen production capacity by 2030 in partnership with industry. Lower carbon heating and cooking with no change in experience for domestic consumers through hydrogen blends and reducing the emissions of the gas used by up to 7%.	Support for up to 8000 jobs by 2030, potentially. Unlocking up to 100,000 jobs by 2050 in a high hydrogen net-zero scenario. Over GBP 4 billion of private investment in the period up to 2030.Savings of 41 $MtCO_2e$ between 2023 and 2032, or 9% of 2018 UK emissions.
Delivering new and advanced nuclear power	Key role for nuclear in delivering deep decarbonisation of electricity system, alongside renewables and other technologies. High-skilled jobs created and sustained across the UK likely role for AMRs in decarbonising industry, heat, and transport.	A large-scale nuclear power plant will support a peak of around 10,000 jobs during construction. Government support could unlock significant private investment, up to GBP 300 million for development of small modular reactors alone. Each GW of nuclear power generation is enough to power 2 million homes with clean electricity.
Accelerating the shift to zero-emission vehicles	Realising carbon savings of around 300 $MtCO_2e$ to 2050 thousands more ultra-low and zero-emission cars and vans on UK roads, supported by additional funding for plug-in vehicle grants. Thousands more charge points in homes, workplaces, residential streets, and along motorways and major A roads.	Support for around 40,000 new jobs in 2030 around GBP 3 billion of private investment by 2026. Savings of around 5 $MtCO_2e$ to 2032 and 300 $MtCO_2e$ to 2050.
Green Public transportation, cycling, and walking	Plans to bring 4000 zero-emission buses onto the UK's roads, representing 12% of the local operator bus fleet in England. Plans to further electrify regional and other rail routes. Plans to launch the first-ever National Bus Strategy, as part of the PM's GBP 5 billion funding, integrated ticketing between operators and modes and more bus lanes, making services faster, more attractive, and cheaper to operate. Plans to spend GBP 500 million reopening lines and stations closed under the Beeching cuts. Plans for over 1000 miles of safe and direct cycling and walking networks delivered by 2025, with network plans developed and being built out in every town and city in England.	Up to 3000 jobs by 2025. Government investment of GBP 5 billion in buses, cycling, and walking this parliament. Savings of around 2 $MtCO_2e$ from green buses, cycling, and walking between 2023 and 2032.
Jet zero and green ships	The production of sustainable aviation fuels in the UK, supporting industry and driving fuel uptake. Plans to cement the UK's position as a global leader in aerospace (worth GBP 12 billion to the UK economy) and position the UK at the forefront of the zero-emission aircraft revolution.	Up to 5200 jobs supported by a domestic SAF industry. Future-proofing the aerospace industry, which is worth GBP 12 billion to the economy. Savings of 1 $MtCO_2e$ by 2032 from clean maritime and nearly 15 $MtCO_2e$ by 2050 from SAF.

Table 1. *Cont.*

Policy Area	Policy Impact	Potential Benefits Delivered
Greener buildings	Set an ambition of 600,000 heat pumps installations per year by 2028. Homes built to the Future Homes Standard will be "zero-carbon ready" and will have 75–80% lower carbon dioxide emissions than those built to current standards green home finance initiatives to help improve the energy efficiency of around 2.8 million homes, improving around 1.5 million to EPC C standard by 2030.	Support for around 50,000 jobs in 2030 around GBP 11 billion of private investment in the 2020s. Savings of 71 $MtCO_2e$ between 2023 and 2032, or 16% of 2018 UK emissions.
Investing in carbon capture, usage, and storage	Ambition to capture and store 10 Mt of CO_2 per year by 2030—the equivalent of taking around 4 million cars off the road. Facilitate the deployment of Carbon Capture, Usage and Storage (CCUS) in 4 clusters by 2030.	Support for around 50,000 jobs by 2030 up to GBP 1 billion of public investment by 2025. Savings of around 40 $MtCO_2e$ between 2023 and 2032, or 9% of 2018 UK emissions.
Protecting our natural environment	Increasing the Green Recovery Challenge Fund to GBP 80 to deliver over 100 nature projects are delivered on the ground over the next 2 years. New National Parks, Area of Outstanding Natural Beauty (AONB) designations, and Landscape Recovery projects will protect up to an additional 1.5% of natural land in England, contributing to our target of protecting 30% of UK land by 2030. Establishing 10 Landscape Recovery projects could create the equivalent of well over 30,000 football pitches of wildlife-rich habitat. Investment in flood defences will support 2000 flood schemes across every region of England and will better protect over 336,000 properties from risk of flooding.	Up to 20,000 jobs from improving flood defences by 2027. Up to GBP 5.2 billion in investment for flood defences. Climate and biodiversity benefits from protecting our national landscapes.
Green finance and innovation	By 2030, unlock the potential for 300,000 jobs in exports and domestic industry through new commercial opportunities across low carbon sectorsenables savings across low carbon sectors.	The potential for hundreds of thousands of jobs by 2030. GBP 1 billion of government funding in net-zero innovation with GBP 1 billion of matched funding and potentially GBP2.5 billion of follow-on funding from the private sector. Carbon savings across low carbon sectors.

It is important to keep in mind that energy transition is a complex problem and is often referred to as a wicked problem [87,88], which requires well-structured policies and effective communication between all stakeholders involved in order to achieve the objective of the planned energy transition policies easier [27]. Reference [1] demonstrates relationships within an energy system in relation to their transformation, considering the complexity of energy transition policymaking as illustrated in Figure 3 below above. Furthermore, energy transition is interlinked to all sectors of policymaking on both governmental and local levels alongside being influenced by external factors such as special interests of industries [5,13,15–20].

Reference [27] highlighted that policy design challenges related to energy transition in the UK in relation to the socio-technical side is highly connected to the complexity and plethora of stakeholder involved in the energy system. The focal take-home point from [27] is that one of the major challenges to enabling energy transition can be associated with the lack of cross-sector agreement between the multiple stakeholders involved and associated with the energy system to support and agree upon a legitimate decision and pathway towards a decarbonization strategy for the UK.

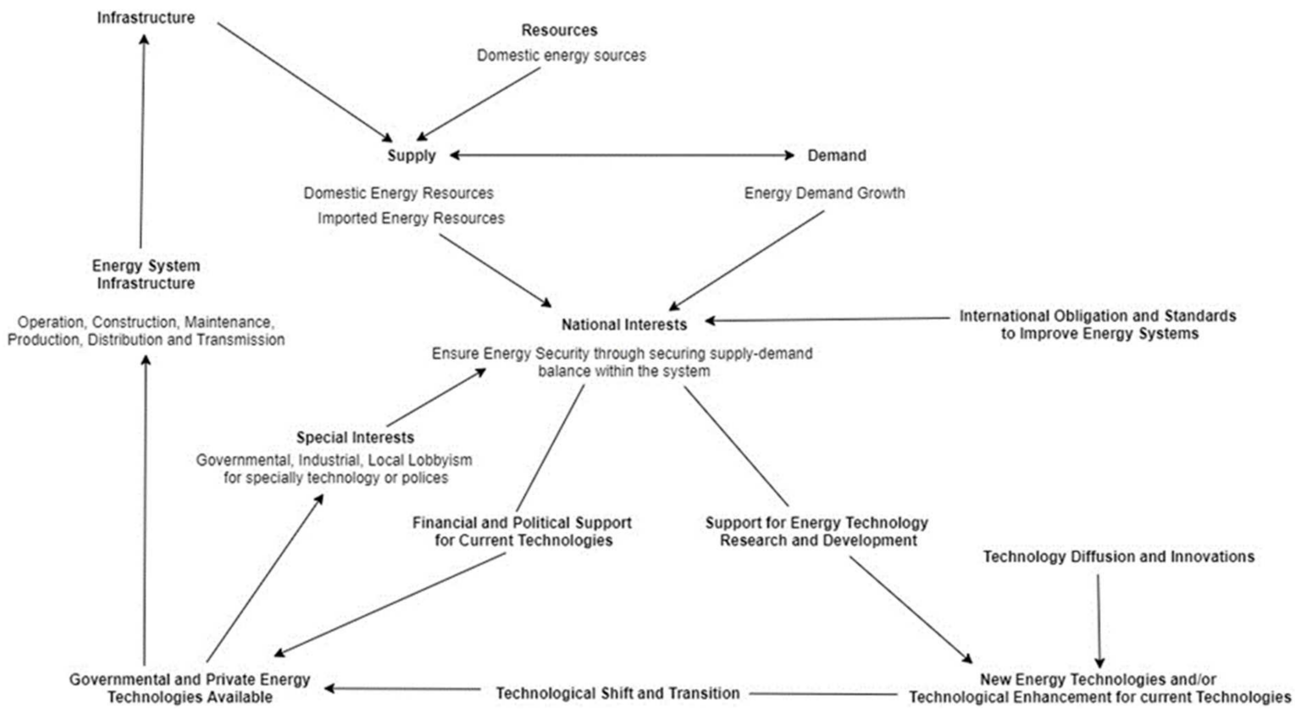

Figure 3. Simplified Explanation of variables and interrelationships in relation to Energy System Evolvement (Adapted from [1]).

References [89,90] highlighted the complexity of energy transition policymaking by emphasizing the interlinking and complex relationships between the energy system and the three dimensions of sustainability. The focal point is the articulation of the internal components of the three dimensions of sustainability; for instance, that society encompasses internal components that are vital for social development such as employment, population, public health, educational system, injustices and inequality, and societal infrastructure. The environment dimension encompasses internal components such as water and land, minerals and fossil fuel resources, climate changes and emissions, and the economy dimension encompasses production, technology, investments, and governments and households.

Reference [88] discussed that even though energy transition policy and strategy making has been moving towards a more comprehensive and broader viewpoint grounded in sustainability and sustainable energy development, it is often looked at solely from a technological perspective and less often from a geographical, social, or temporal viewpoint [88]. Technology plays a vital part in energy transition, and technology advancements are key to overcoming challenges such as the intermittency of renewable energy sources, which is a key obstacle to a successful energy transition [88–90]. The intermittency challenges of RES can prove to be a significant obstacle for energy systems that are heavily dependent on fossil fuel exports and/or do not have a diversified portfolio of energy resources within the national and regional supply chain [77]. This impacts production capabilities and supply security, thus creating potential instability within the energy system [87]. Another challenge for energy policymakers is urban energy transition (a system change that focuses on changing energy technologies and fuel sources towards low carbon and cleaner energy technologies and fuel sources without weakening the energy systems abilities to satisfy the energy demand of their urban area [1,75]), where the challenges range from development and refurbishment of infrastructure and buildings within the cities [84,87] to the increasing urbanisation rate with the prediction of 70% of people living within urban areas by 2050 [83,84].

The energy transition is facing various challenges from social and political perspectives as well. As [91] points out, one of the major challenges for a successful energy transition is often a lack of social acceptance of the energy transition and development plans on a national or regional level. Likewise, the political landscape and political acceptance on both national and urban levels can be an obstacle to energy policies and decision-making toward fostering energy transition [92–97]. This paper focuses on highlighting some of the challenges for energy transition policy design concerning the Tees Valley energy system in the context of the UK energy transition policies.

2.4. Review of Application of System Dynamics in Analysing Complex System Changes and Development

This study aims to highlight the complexity of energy transition policy design in relation to the localised energy system through gaining (i) an understanding of the application method used to assess complex system, (ii) insight into the dimension included in modelling within the context of energy transition and policy design, and (iii) understanding the volume of modelling variables include in system dynamics models when looking at multi-layered and complex problems.

An extensive structure review and content analysis of 106 papers were carried out, which allowed for a broad perspective on the topic of the complex problem of energy transition that helps in gaining the understanding to provide insightful knowledge concerning the objective of this study. The framework used to analyse the papers, alongside meta-analysis figures from the analysis, are presented in Appendix A, Figures A1–A3, and Table A1.

Application of the system dynamics approaches to analyse topics that are classified as complex systems, such as energy system transition and development and policymaking, has been used since the 1960s and has become more significant and relevant in recent decades [38–45]. Reference [90] presented a technology sustainability assessment framework that integrates technology development, sustainable development, and a system dynamic approach focused on improving the ability of technology developers to understand the negative and positive impacts of their technology and help to improve sustainable energy technology policy implementation. Reference [47] presented an integration of the system dynamic approach with a life cycle sustainability assessment framework, which would provide a new generation modelling tool that is enabled to quantitatively assess the economic, social, and environmental spheres of sustainability. This can help enhance the decision and policymaking process, which was used to investigate and analyse complex dynamic relationships and impacts across the three spheres of sustainability in the context of transportation sustainability and implementation of alternative fuel vehicles. Reference [50] applied a system dynamic approach to the sustainability assessment of biodiesel production in Colombia, where they investigated the sustainability of biodiesel production at the national level to provide information and improve the understanding of its negative and positive environmental, social, and economic potential impacts of biodiesel production and infrastructure development in Colombia to help improve the decision-making process.

Many of these papers investigate infrastructure development and related policy implementation. Reference [98] applied a sustainability assessment implemented through the utilisation of system dynamic modelling to enhance the decision making and asset management in relation to wastewater infrastructure. The model applied involved 40 variables and covered the economic, environmental, and technological aspects of asset management. The results from that study illustrated that focusing on the rehabilitation of assets would result in low economic costs and provide the lowest GHG emission over the period considered. The study also shows the opportunity and benefits gained from long-term scenario simulation and the application of system dynamics modelling to decision-makers as they can run and test different scenarios over various timeframes. Reference [99] applied system dynamics integrated with a sustainability assessment (henceforth referred to as the SDSA approach) to assess the overall sustainability of the development of seaports clusters in terms of regional economic impact, social impacts, and environmental impacts, to provide insights that can be used to enhance decision making when it comes to seaport development in the future. Reference [100] applied an SDSA approach to analyse the impacts of urban activities to understand the larger impacts and the causal effect relationship between social activities on the local scale and social activities on a regional scale to improve decision making concerning residential development. Reference [101] developed a sustainability assessment framework using stakeholder engagement and performance indicators alongside system dynamic modelling and a distributed zoning approach to assessing the sustainability and management of integrated water resources systems to support policymaking and ensure better utilisation of water resources.

As shown in Figure 4 below above, most of the selected papers focus on investigating problems related to energy or infrastructure in the context of sustainability. Reference [54] applied a system dynamic modelling approach to understand Beijing's energy consumption and CO_2 emission trends that span over 25 years. The result of this study provides insights into energy consumption and emission trends in relation to different sectors within the city, which is vital for Beijing's future energy and emission planning. Reference [102] applied a system dynamic modelling approach to assess the policy on increasing renewable energy in Colombia and understand the effects of their increase on the energy system and its reliability. The paper's results highlight that RES positively affects the energy systems and contributes to increasing energy security in Colombia, especially during low rain seasons. Reference [9] applies a system dynamics approach to model the supply and demand mechanism of Ecuador's energy system and CO_2 emission scenarios until 2030. The system dynamic model was used to analyse changes in primary energy production, emissions, and final energy consumption. The results highlighted that energy consumption is mainly associated with transportation and industries and that oil is the most important source of energy within the energy system. The results and insights from the study were used to help propose energy policies targeted at emission mitigation.

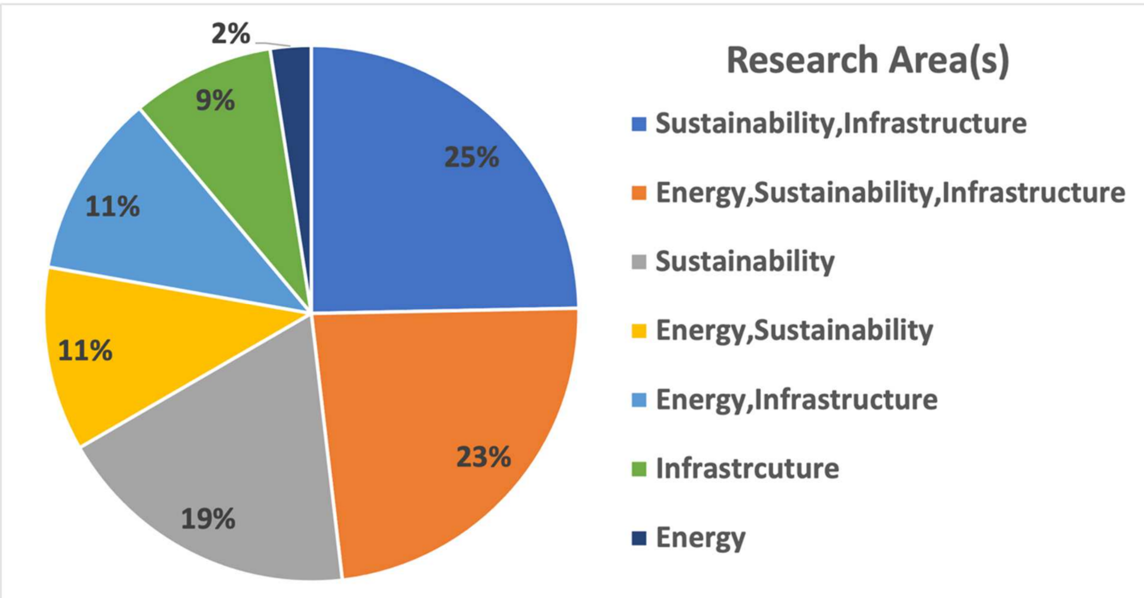

Figure 4. Research area focus among the review papers.

3. Methodology

3.1. Methods

This paper applied two research methods to understand and illustrate the complexity that policymakers face when designing energy transition policies in the context of regional and urban energy planning and development. The first method is an extensive structure literature review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline published by [103]. The application of an extensive structure review approach based on PRISMA provides a robust, comprehensive data collection and analysis process to identify and analyse the literature relevant to a specific area of research [60,103–105]. It also helps in providing an extended overview of research conducted within that specific area [60,103,104]. The PRISMA guideline presented by [98] has four key steps: identification, screening, eligibility, and inclusion.

The second method is the Causal Loop Diagram (CLD), a System Dynamic Methodological approach. CLD is a method used by system dynamic partitioners to map out and conceptualise the problem and the system that is being investigated to finally provide a visual representation of the system and its important elements along with their causal relationship and feedback loop [47,106,107]. CLD is a crucial modelling method in SD methodology that focuses on drawing up and qualitatively investigating feedback loops and dynamic relationships within the problem being analysed [38,39,90,107,108]. The application of CLDs allows for an illustrative mapping of the complexity and dynamics of energy transition in the context of sustainability, along with allowing for the conceptualisation and visualisation [38,39,90,107] of the challenging and multifaceted problem policymakers face in the development of energy transition policies. Thus, CLDs provide a more in-depth insight into the challenging policy-making environment is in relation to energy transition and energy system development.

Although there is an overlap in the application of these two approaches, an eight-step research process was constructed to ensure the development of a comprehensive macro-level dynamic modelling diagram representing the Tees Valley energy system and the complex dynamic relationships within the system.

3.2. Research Process

Figure 5 depicts the eight-step research process, which is divided into two core research activities, the extensive structure literature review process and the system dynamics approach.

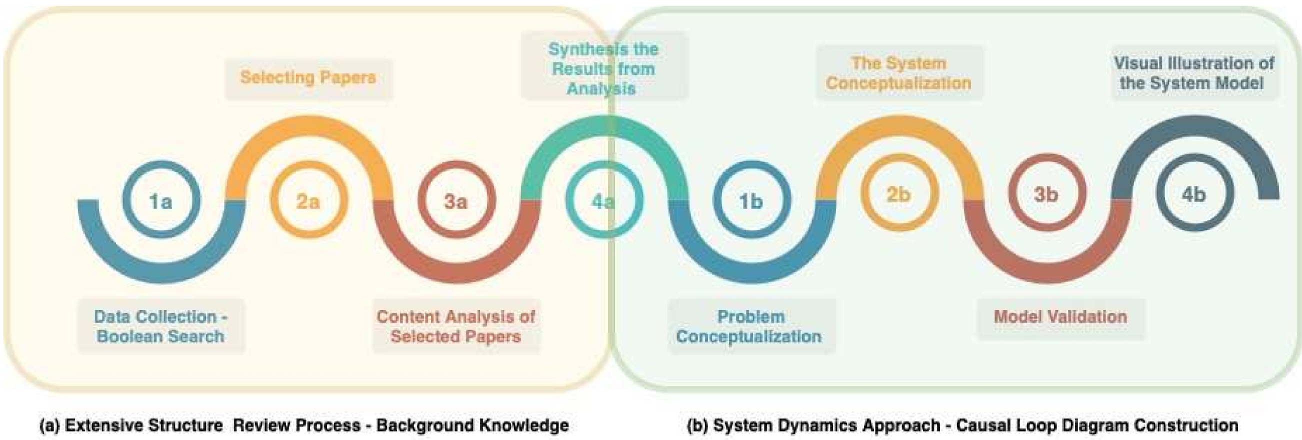

Figure 5. Illustration of Research Process.

3.2.1. Extensive Structure Literature Review—Selecting Papers and Content Analysis

The extensive structure literature review approach adopted for this study follows a similar process with steps as listed below:

Step (1a) Data collection and identification of papers by conducting the Boolean keyword search.

Identification of papers was conducted using keywords search within selected databases. The databases used in this study were Scopus and Google Scholar. Six keywords were used for the Boolean search, namely "System Dynamics", "Sustainability Assessment", "Urban Energy System", "Energy Transition Policy", "Decision Making", and "Policy-Making". The papers identified were collected and formed the data used in the next steps of the systematic review process.

Step (2a) Selecting and filtering out papers.

The screening and assessment of papers' eligibility followed a five-step filtering process: Step (a)—filtering and removing duplicates; Step (b)—removing non-academic journal papers (e.g., thesis, reports, etc.); Step (c)—removing papers by reviewing keywords and abstracts; Step (d)—reviewing the papers and their relevance to the topic and focus of this study; lastly, Step (e)—the final listing of papers included in the analysis.

Step (3a) Content analysis to identify (i) the challenges policymakers are facing in terms of policy design and decision making and (ii) the key variables that should be included in the dynamic model when it comes to investigating energy transition and energy system development in the context of sustainable development.

This stage focuses on content analysis of the selected papers with the objective to understand the complexity that policymakers face when designing and deciding on energy transition and development policy in the context of regional and urban energy system planning and development.

Step (4a) is focused on synthesizing the results from the literature analysis.

The synthesis stage of the systematic review for this study focuses on combining the literature analysis results and using them to construct a visual representation of the dynamic complexity of energy transition and highlighting the complicated situations policymakers face through the application of the system dynamics methodological approach.

3.2.2. Causal Loop Diagram—System Thinking

The approach to developing the CLD for this study follows the steps listed below:

Step (1b) focuses on the problem conceptualisation based on knowledge gained from previous steps.

Modelling variables are identified using the results from the literature review. This focuses on further analysis of papers that presented a CLD or a stock and flow model to identify modelling variables and feedback relationships.

Step (2b) focuses on the system conceptualisation and identifying the causal and feedback relationship within the model between different variables.

This step focuses on constructing the CLD for the Tees Valley energy system focusing on utilising results from step (1b) to understand and clearly define the causal relationships between different variables within the model.

Step (3b) is modelling validation to confirm the different relationships within the model and the reliability of the modelling relationships presented, which is carried out based on the published literature in the case of this study.

The validation process for the CLD model is structured around literature-based validation. The literature analysed in the previous steps is utilised to confirm the selection of variables presented in the model and validate the causal relationships between different variables in the model. Additionally, an internal validation process was also used to confirm the relationships and selected modelling variables.

Step (4b) is a visual presentation of the results to highlight the challenges policymaker faces in energy transition and energy system development in the context of sustainability and sustainable development.

This last step focuses on presenting the system model through the application of the CLD, highlighting the different variables, their categories, relationship, and causalities.

3.3. Case Study Area—Tees Valley Energy System

Tees Valley is in the North East of England and has a population of 667,400, spread across five local municipalities: Darlington, Hartlepool, Middlesbrough, Redcar and Cleveland, and Stockton-on-Tees. These five local authorities have, since April 2016, been represented by a joint authority—the Tees Valley Combined Authorities (hereafter TVCA) [30–33]. Table 2 below provides an overview of the Tees Valley energy system. Within the regional boundaries of the TVCA are five power plants with an overall production capacity of 1449.3 MW. The dominant technology used is nuclear energy which accounts for 81.7% of the energy production capacity.

Table 2. Information on the Energy System in the TVCA, showing location, Fuel, Type, MW Capacity (Derived from [109]).

Location	Operator	Plant Name	Fuel	Type	Capacity (MW)
Redcar and Cleveland	EDF Energy	Teesside	Wind (Offshore)	Wind (Offshore)	62
Hartlepool	EDF Energy	Hartlepool	Nuclear	AGR	1185
Middlesbrough	Sembcorp Utilities	Wilton 10	Biomass (virgin wood)	Bioenergy	33.3
Middlesbrough	Sembcorp Utilities	Wilton GT	Natural Gas	Conventional steam	120
Middlesbrough	Sembcorp Utilities	Wilton 11 EfW	Waste (municipal solid waste)	Bioenergy	49

As such, the Tees Valley region is characterised as a high energy intensity area due to the concentration of energy-intensive industries operating in the area. Tees Valley is considered one of Europe's largest industrial zones that host both energy-producing and high energy-intensive industries [30–33]. Figure 6 presents a simplified illustration of the Tees Valley energy system.

The dotted blue line in Figure 6 below indicates the boundaries of the local energy system. There are three low carbon energy technologies operating in the area, bioenergy, nuclear and wind energy. The fossil fuel technology operating in Tees Valley is natural gas. The relationship between the regional energy system and the UK's national energy system is illustrated with the black dotted lined box. Together these two sections represent the supply side of the energy system. The demand side of the energy system is presented within the red dotted line. The demand section is constructed out of three elements—population, commerce, and industry.

The highest concentration of industrial activities in the Tees Valley region is in Redcar and Cleveland and Stockton-on-Tees. These two municipalities account for approximately 76% to 86% of the annual CO_2 emission from the region between the years 2005 and 2018. Figure 7 below shows the region's CO_2 emission pattern between 2005 to 2018 [30–33].

Over the recent decades, the Tees Valley region has had a significant number of closures of large industrial complexes operating in the area, which has resulted in a rapid decrease in CO_2 emissions across all areas of the TVCA region [30–33], declining from 12 tons to 3.47 tons of CO_2, which is a decrease of 71% between 2005 and 2018. Emissions from domestic electricity also decreased from 0.6 tons to 0.24 tons of CO_2, which is a decrease of 59% between 2005 and 2018 [30–33]. The total CO_2 emission of the Tees Valley region has dropped by an astonishing 60% between 2005 and 2018 [30–33].

Although Tees Valley's energy system has been experiencing a positive transition in terms of reduction in CO_2 emissions, this has been brought on via industrial closures in the area. Besides, the industrial and commercial sector in the region still accounts for 68% of CO_2 emissions. Furthermore, Tees Valley still produces most of its energy from nuclear, which is a debated energy source when it comes to the mitigation of climate and ecological impacts of energy systems [30–33]. In recent years, the focus of TVCA has been on a clean and renewable energy transition through increased investment into research in the fields of hydrogen production and carbon capture and storage, alongside approving the construction of the Dogger Bank wind farm. Dogger Bank will have three offshore wind farms, each with a generation capacity of 1.2 GW, thereby increasing the energy generation capacity of Tees Valley by 3.6 GW when completed [30–33,110]. These focus areas are in line with the UK government's policies for energy transition mentioned in Table 1 above, such as *advancing the offshore wind capacity*, *driving the growth of low carbon hydrogen*, *green finance and innovation,* and investing *in carbon capture, usage and storage*. Nevertheless, policymakers at TVCA still face a multifaceted and complex problem when it comes to enabling Tees Valley's energy transition towards a decarbonised energy system in ensuring that those projects and plans provide societal growth and development in the region.

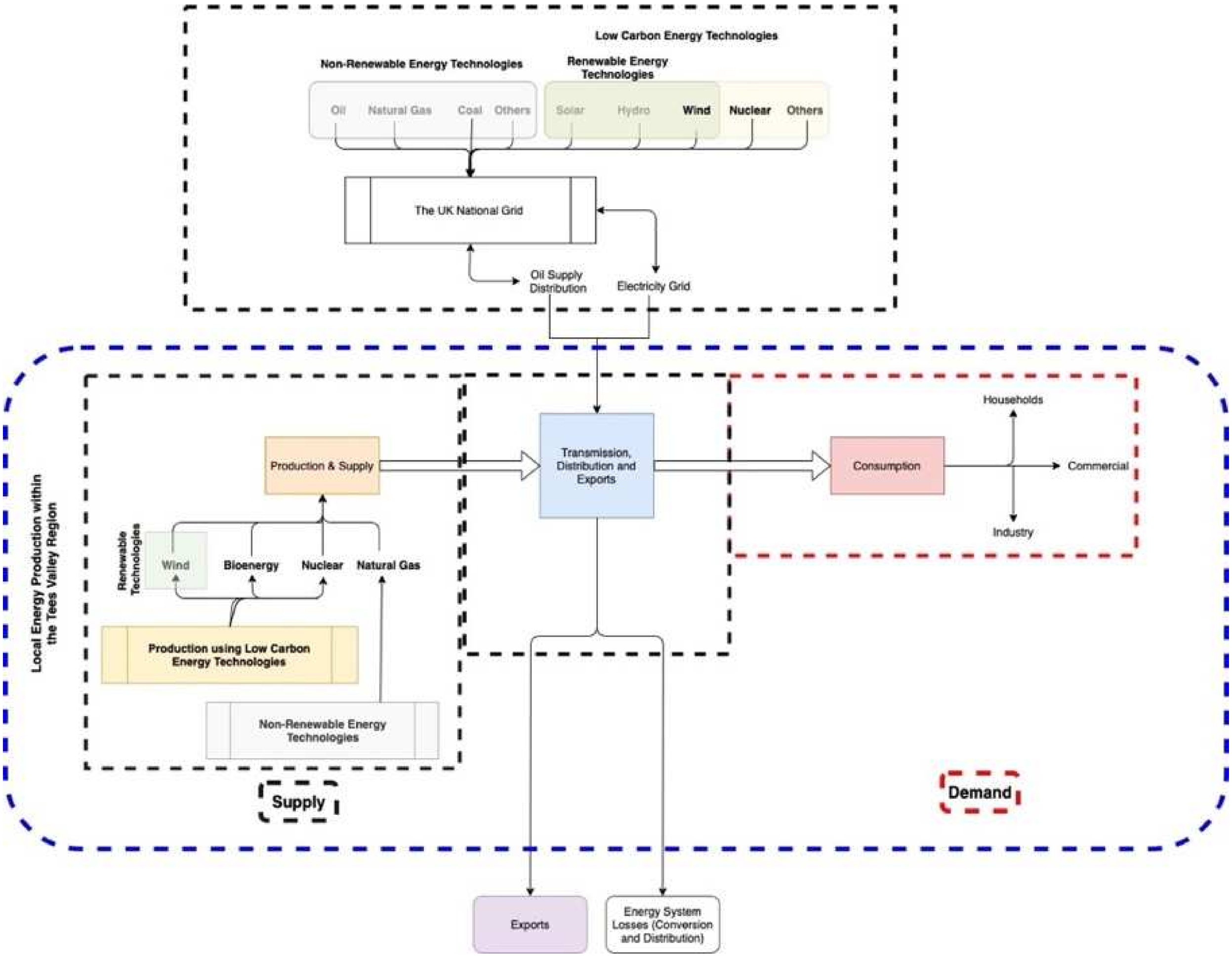

Figure 6. Simplified Illustration of TVCA Energy System, flow of energy, and relationship between Supply and Demand.

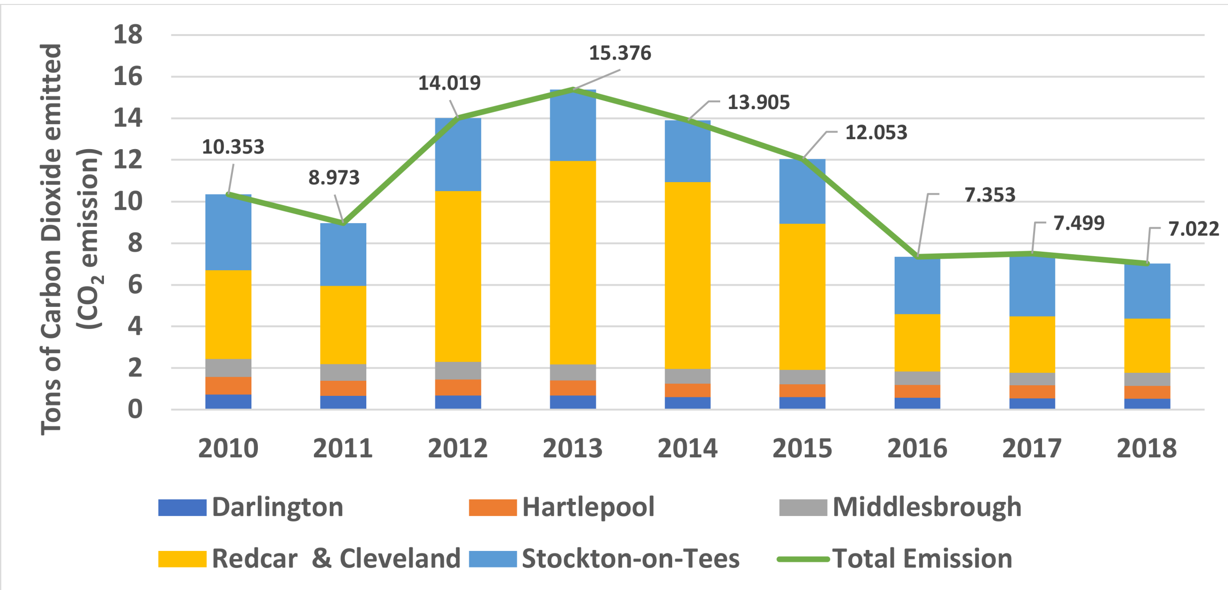

Figure 7. CO_2 Emission from the five local authorities in Tees Valley (Derived from [30–33]).

4. Results and Discussion

4.1. Content Analysis to Highlight Complexity of Energy Transition Policy Design

Content analysis was applied to identify the modelling dimensions across the selected papers to understand the key modelling dimensions for investigating complex problems such as the energy transition. Whether the application of system dynamics modelling to complex problems require a broader view on top of the traditional dimensions of sustainability, namely environment, social, and economic, was also checked. Over the last 30 years, a consensus has formed around those three dimensions being the core dimensions of sustainability within international society and the academic literature [35,77,82,83,100,111]. This places them at the foundation when it comes to strategic decisions and policymaking concerning energy transition and sustainable energy development [77,82].

Table 3 illustrates that most of the selected papers include at least two of those three traditional sustainability dimensions within a system dynamic model. Moreover, close to half of the reviewed papers include a technology dimension in the model in combination with one of the traditional sustainability dimensions.

Table 3. Count of Modelling Dimension applied in the reviewed papers.

Dimensions	Definition	Number of Papers
Economic	This dimension focuses on capturing the economic variables and relationships which help in understanding economic conditions and effects in relation to energy transition and investments and economic incentives such as the cost of investment into new energy technologies.	88
Environment	This dimension focuses on capturing the environmental variables and relationships, which help in understanding environmental both positive and negative impacts associated with the energy transition, such as greenhouse gas emissions and air pollution.	79
Social	This dimension focuses on capturing societal variables and relationships, which can help understand the social effect and impacts associated with the energy transition, such as job creation and populations growth.	75
Technology	This dimension focuses on capturing technology variables and relationships, which can help understand the effect of technology and the core relationship between technology and other dimensions that enable and impact energy transition, such as operational lifetime, installed capacity, and energy production.	48

Table 4 presents the different combinations of dimensions used in system dynamic modelling across all the reviewed papers. The most common dimension combination is a combination of the traditional sustainability dimensions (economic, social, and environment). The second most common one is the combination of four dimensions structured around integrating technology with the traditional sustainability dimensions. This reinforces the fact that when looking at energy system transitions and development, technology should be considered as the fourth dimension of sustainability. After all, technological development and energy technologies are key elements of any energy system and its development [90]. Reference [90] discussed that acknowledging the interrelationship between technology and the different dimensions is a key factor in successfully integrating a technology dimension into the system dynamic model since the technology itself cannot determine the future aspects of sustainability in any of the other dimensions. However, the interrelationship between technology and other dimensions affects each other. Modelling these factors helps to understand the impacts and effects that technological elements such as technology development and diffusion can have on energy systems and the energy transition. This justifies the inclusion of technology as the fourth dimension in the proposed dynamic model for the Tees Valley Energy System, which is presented and discussed in the next section of this paper.

The results of the content analysis presented in Table 4 above and Table 5 below shows insights into the complexity associated with the energy transition and policy design making. It should be highlighted that the complexity of the energy transition is expressed via a high variation in modelling variables used across selected papers analysed. The majority of the system dynamic models presented in the papers are classified into two clusters (a) Cluster A includes the models that have between 0 and 30 modelling variables across all the dimensions in the model, and (b) Cluster B includes models that have between 31 and 60 modelling variables across all the dimension in the model. This affirms the high degree of complexity and emphasises that energy transition policy and decision-making need to cover a significant number of variables across societal, economic, environmental, and technological dimensions. This complexity is constantly faced by policymakers when it comes to policy design for energy transition pathways.

Table 4. Combination of Modelling Dimensions.

Dimensions Combination	Number of Papers	Paper ID Reference *
Economic + Environment + Social	18	[3,4,9,11,13,14,23,24,30,32,33,35,36,41,64,67,69,75]
Economic + Environment + Social + Technology	16	[2,6,8,17,18,25,28,40,44,57,58,63,65,74,76,77]
Economic + Technology	10	[16,26,48,61,62,70–73,78]
Economic + Environment	5	[10,27,37,46,49]
Social + Environment + Technology	5	[34,42,45,51,52]
Economic + Environment + Technology	4	[4,19,53,54]
Economic + Social + Technology	4	[14,56,59,68]
Economic + Social	3	[29,47,66]
Technology	3	[43,79,80]
Social + Environment	2	[7,38]
Economic	2	[22,31]
Environment + Technology	2	[1,60]
Economic + Environment + Social + Technology + Political	1	[20]
Social + Technology	1	[50]
Social	1	[12]
Institutional and Policy	1	[21]

* (See Table A1 in Appendix A for Paper IDs).

Table 5. Clustering of Models by Number of Modelling Variables in Model.

Cluster ID	Number of Modelling Variable	% of Selected Paper
A	Variables in a Model—0 to 30	51
B	Variables in a Model—31 to 60	33
C	Variables in a Model—61 to 90	19
D	Variables in a Model—91 to 120	3
E	Variables in a Model—121 to 150	3

The results presented above also highlight that a transition toward a decarbonised energy system is not only an economic or technical problem but a problem that is intertwined in all fabrics of human society and the natural world since it requires decisions and pathways to take into consideration: several societal aspects such as human development and prosperity [47,112,113]; the economic aspects in terms of the costs of the transition, economic growth and ensuring affordability of energy to all [12,37]; and technological aspects such renewable infrastructure development, suitability of technology to geographical location, and technology advantages gained from increasing knowledge and innovation [114,115]. Finally, these decisions and pathways need to be designed with the environmental aspects and boundaries of our planet in mind, meaning that these pathways should be implemented without increasing the ecological degradation caused by the current energy system and past energy strategies that focus on burning and extraction of conventional energy resources [98,100,112,115].

4.2. Conceptualisation of the Complexity of Energy Transition Policy Making

Figure 8 below visually illustrates the complexity of energy transition policy and decision making and presents the interconnectedness between the four dimensions: social, economy, environment, and technology. Behind those four key dimensions lies even more complexity, such as when looking at the social dimension, e.g., population demography [112,116], public health and well-being [111,117], employment [113,118], energy security [119], affordability, and improving urban living [35,117] are all key areas that the energy transition needs to be incorporated and covered in future energy transition policies. By looking at the economic dimension, areas such as economic growth [40,100], technology and infrastructure investment [12,35,120,121], energy consumption [122,123], and energy price [50,124] can be considered as key areas and are highly interconnected and affect other key areas such as affordability and employment in the social dimension. The key areas when it comes to the technological dimension are renewable technologies [12,40,117,122], technological development [12,40], demand response technology and software [121] distribution, and transmission technology development [98]. The technology dimension and its factors are often highly impacted by the economic landscape within each nation and country. By looking at the environment dimension, the key areas within this dimension are related to the mitigation of climate change [9,12,125], limiting the environmental degradation and impacts of energy infrastructure development [99,126], and ensuring global biodiversity and prosperity of natural ecosystems [50].

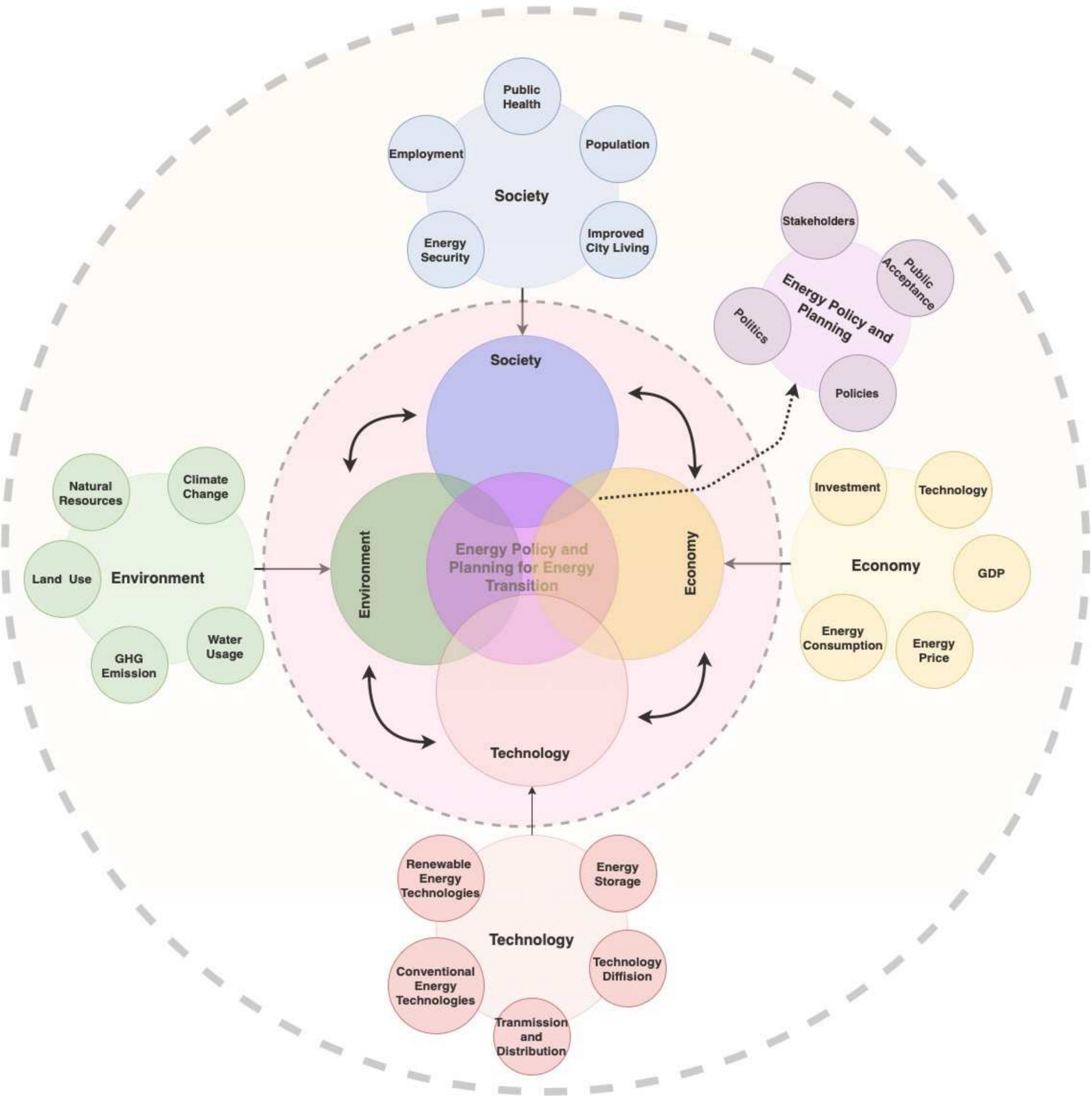

Figure 8. Interrelationship and Complexity of Energy Transition Policy Making (adapted from [127]).

The System Boundary and Structure

The completion of the literature analysis completed the conceptualisation of the complexity of energy transition, and policymaking was completed. The next step was to define the system boundaries based on the literature analysis and conceptualisation of the energy transition policy settings. The system boundaries were defined alongside determining the relevant variables and sub-sections that can represent energy transition policy and decision making in the Tees Valley region, highlighting the complexity that policymakers are facing when it comes to selecting energy transition pathways. Figure 9 illustrates the system boundaries, sub-sections, and relevant variables and highlights the interconnections between different sub-sections.

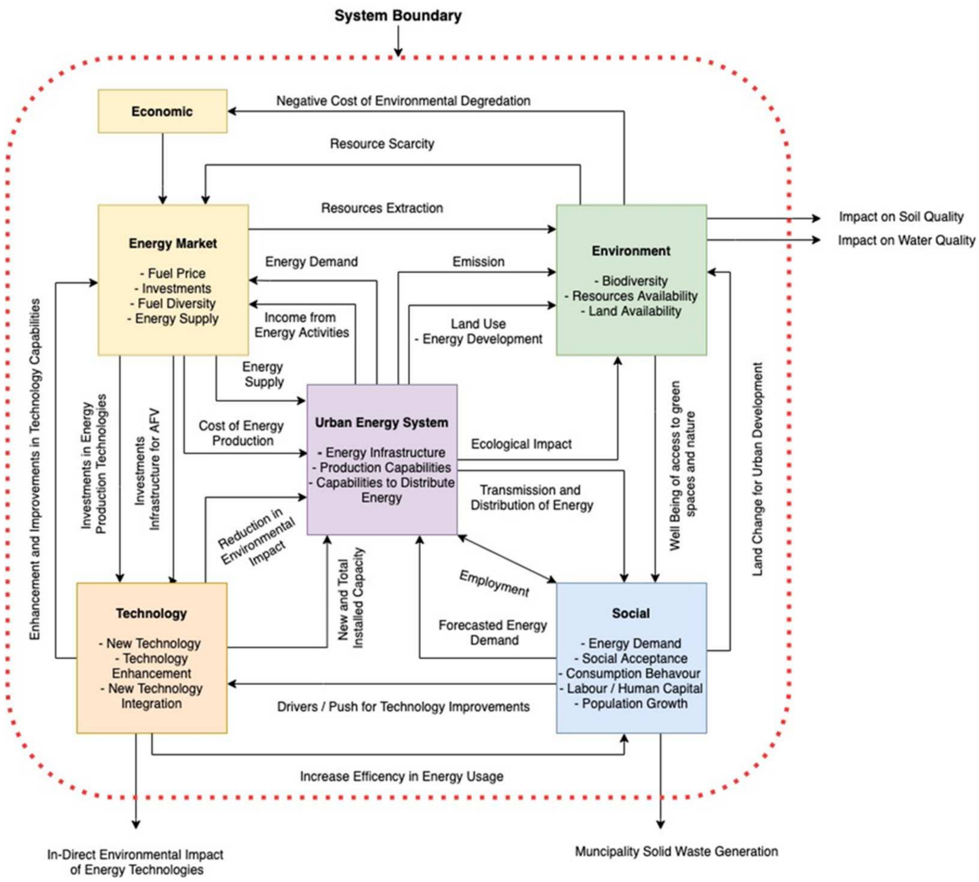

Figure 9. Illustration of the modelling boundary and interconnection between dimensions and different variables.

A good and clear definition of the system boundaries, sub-sections, and variables is crucial when constructing a CLD. The conceptualisation of the complexity of energy transition in the Tees Valley Energy system identifies modelling dimensions for the CLD and the key variables, which is vital to ensure the CLD captures the aspects and characteristics of the Tees Valley Energy System.

4.3. Causal Loop Diagram Design

This section presents the CLD model that illustrates dynamics and interrelationships within the Tees Valley energy system. Table 6 below illustrates all the modelling variables represented in the Tees Valley energy system CLD, shown in Figure 10. It provides core information and valuable elements for the development of a computerised system dynamic model, which can be used to assess the economic impacts of the energy transition on the Tees Valley region.

Table 6. Modelling Variables Information.

Variable	Dimension	Definition	Variables Type	Reference *
Energy Demand	Technology	MW	Endogenous	[17,30,34,46,49,51,63,75]
Energy Price	Economic	USD/KWh	Market Variable	[20,48]
GDP	Economic	Million (GBP)	Endogenous	[9,11,19,23,24,29,33,36,40,41,46,49,51,63]
Investment in Renewable Energy Technology	Economic	Million (GBP) per MW capacity	Endogenous	[14,26–28,51]
Investment in Fossil Fuel Energy Technology	Economic	Million (GBP) per MW capacity	Endogenous	[14,26,27,51]
Energy Costs	Economic	USD per producing one unit of MW	Endogenous	[22,31,51]
Cost of Investment in RENEWABLE ENERGY Technologies	Economic	Million (GBP)	Endogenous	[11,36,40,51]
Cost of Investment in Fossil Fuel Energy Technologies	Economic	Million (GBP)	Endogenous	[11,36,40,51]
Attractiveness for Industry to come to Tees Valley	Economic	No. New Businesses	Market Variable	[13]
Industrial Activities	Economic	Output from Industries	Endogenous	[7,17,42]
Greenhouse Gas Emission	Environment	kg CO_2 eq./KWh	Endogenous	[4,6–8,19,20,30,31,42,46,51,58,75]
Climate Change	Environment	tons CO_2 eq	Endogenous	[23,51]
Policies for Climate Change Mitigation	Environment	Qualitative [0,1]	dmnl	[7,44,46]
Population	Social	No of People	Exogenous	[4–6,8,11,15–17,19,20,23,24,33,34,36–38,40,47,58,63]
Population Change	Social	No of People	Exogenous	[6,8,11,14,24,34,36,50,63]
Employment	Social	No of new jobs created	Endogenous	[6,9,15,20,29,41,58,59,63]
Regional Renewable Energy Production Capacity	Technology	MW/year	Endogenous	[20,28,30,31,40,41,45,46]
Fossil Fuel Energy Production Capacity	Technology	MW/year	Endogenous	[20,30,31,40,46]
Attractiveness of Renewable Energy Technology	Technology	Quantitative [0,1]	dmnl	[40,51]
Attractiveness of Fossil Energy Technology	Technology	Quantitative [0,1]	dmnl	[40,51]

* (See Table A1 in Appendix A for Paper IDs).

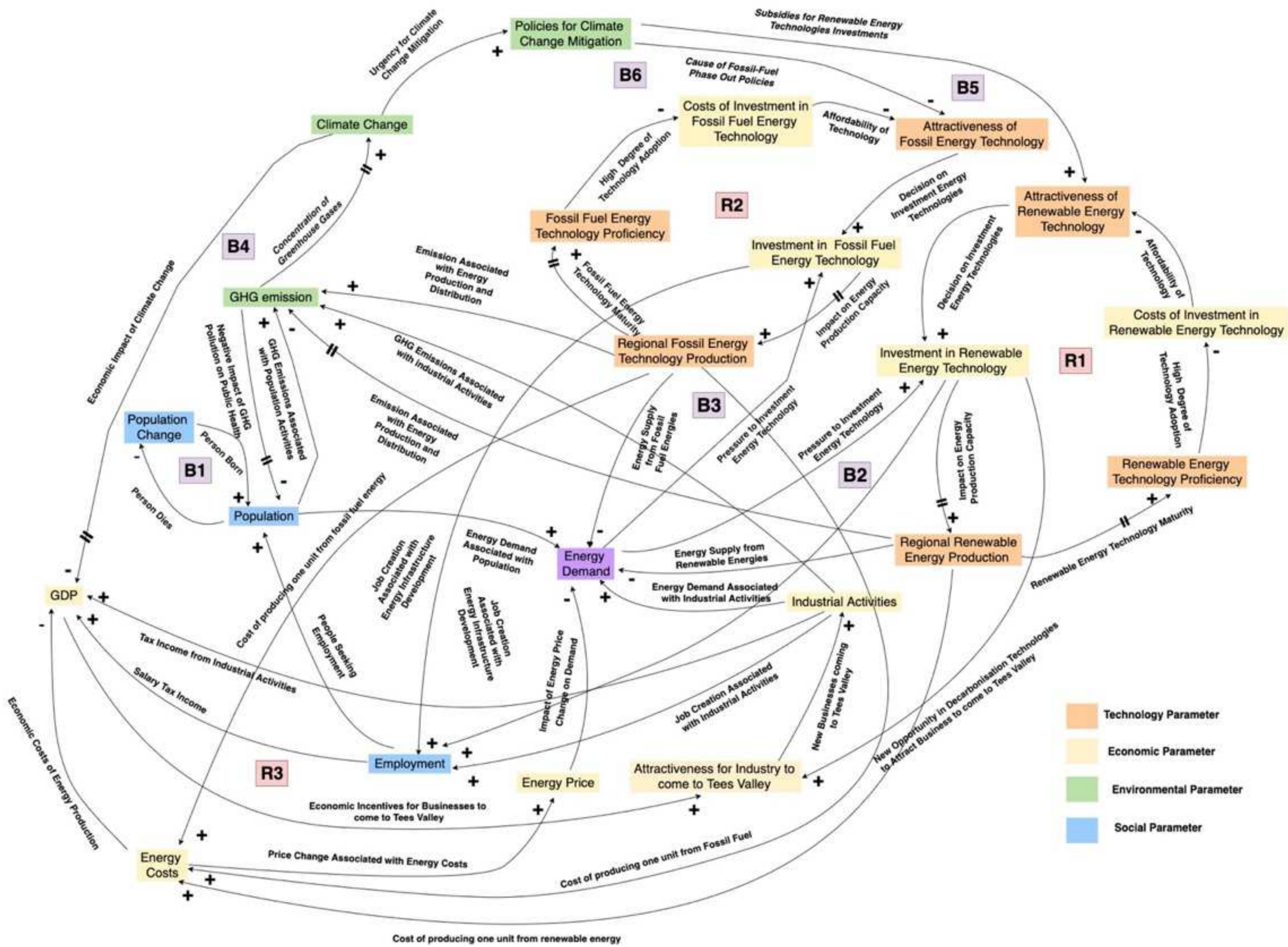

Figure 10. Qualitative-based Causal Loop Diagram of Tees Valley Energy System.

4.3.1. Economic

Understanding and analysing the economic aspects of economic behaviours, trends, and impacts of energy transition of a localised energy system is one of the key elements when it comes to policymaking. This is because understanding the economic expression of an energy system in relation to energy transition provides insights into the short- and long-term economic effects of different policies that can be applied in the e pathways to achieve the energy transition. The economic sub-sections in the proposed CLD model focus on capturing aspects such as energy technology investments, energy costs, energy price, regional income from industrial activities, and their relationships with other dimensions. Table 6 above presents all the economic modelling variables included in the CLD. Illustrating the complex interconnected relationships between economic variables other modelling variables is crucial to help understand the energy transition complexity.

4.3.2. Environment

Understanding and analysing environmental impacts such as GHG emission trends within an energy system is key when it comes to policymaking as achieving a reduction in GHG emission and climate change mitigation ensures that the right policy is implemented. The knowledge of the environmental effect of the energy transition and energy system development in relation to different policy pathways provides insights into how successful various policy instruments and energy developments are in relation to the environmental mitigation impact of energy development. The environmental sub-sections in the proposed CLD model focus on capturing environmental impact activities and the causality between them and energy system development. This sub-section encompasses three modelling variables: GHG emission, climate change, and policies for climate change mitigation.

4.3.3. Social

Understanding and analysing the social aspects of the energy transition such as job creation, public health in relation to GHG emission from the whole energy system, and population demography, especially population change impact of emigration of new employers, are key to policymaking. Knowledge of the short- and long-term impacts, whether direct or indirect, is vital to understanding the societal benefits of energy transition and energy system development. The social sub-sections in the proposed CLD model focus on capturing social aspects, societal activities, and the causality between the social aspects and energy system development. This sub-section encompasses population change and the job creation aspects of energy system development.

4.3.4. Technology

Understanding and analysing the technical aspects of the energy transition, such as technical proficiency, energy production capacity gained from technological investments, the attractiveness of fossil fuel energy technology and RET in relation to energy system development, their impact on energy system performance and stability, are critical when it comes to policymaking. The knowledge of the short- and long-term impacts of technologies, whether direct or indirect, is vital to understanding the effects of energy transition and energy system development. The technology sub-sections in the proposed CLD model focus on capturing aspects such as energy technology proficiency and energy production capacity and the causality between the technological aspects and other dimensions within the present CLD.

4.4. Overall CLD and Dynamic Hypothesis

The overall CLD for the Tees Valley energy system is present in Figure 10 below. The CLD presents a simplified macro-level view of the Tees Valley energy system and highlights the most critical feedback loops (Table 7), along with the most important modelling variables that influence and represent energy system activities (Table 8).

Table 7. Feedback Loops in the CLD.

Reinforcing Loops in the System
R1—Technological Diffusion/Learning = Renewables
R2—Technological Diffusion/Learning = Fossil Fuel
R3—Direct Impact of Economic Growth in relationship Job Creation
Balancing Loops in the System
B1—Population Growth
B2—Drivers for Energy System Investment = Renewables
B3—Drivers for Energy System Investments = Fossil Fuel
B4—Energy Rebound Relationship
B5—Policy Effect = Renewables
B6—Policy Effect = Fossil Fuel

The main assumptions made for the overall CLD are:

(A) Increasing regional energy production capacity for both fossil fuel technology and renewable technology increases the technological know-how within the energy system. This decreases the cost of investment for both fossil fuel and renewable energy technologies, thus making it more attractive to invest in these technologies. This, in turn, increases the energy production capacity. These causal relationships are represented in causal loops R1 and R2;

(B) Policy effects of climate change mitigation policies: The increasing urgency for climate change mitigation pushes for increasing policies that have contrasting impacts on the two energy technologies within the energy system. In the case of fossil fuel technologies, further climate change mitigation leads to a lower attractiveness, which in turn leads to a decrease in investment, thus decreasing the fossil fuel energy production capacities built up in the system. The GHG emissions from fossil fuel-based energy production decrease, thereby leading to a decrease in the accumulated impact and contribution of the energy system to climate change. Meanwhile, in the case of RET, climate change mitigation leads to increasing attractiveness, which in turn leads to an increase in investments, production capacity, and share of energy production within the system. This then reduces GHG emissions from energy production, leading to a decrease in climate change impacts. These causal relationships are represented in causal loops B5 and B6;

(C) Drivers for energy system investment: The energy demand is the main driver, meaning its growth leads to an increase in investments in both fossil fuel and renewable energy technologies in the system, increasing their energy production in the region. As energy production capacity is interlinked to the change in the energy demand, this ensures balance and stability of the energy system. The causal relationships are represented in causal loops B2 and B3.

Table 8 shows the causal relationship and effects between different variables present in the CLD. These relationships and effects were validated by using the published literature in the fields of energy, sustainability, and infrastructure development. This verifies the formatting and soundness of the CLD proposed for Tees Valley and its representation of the energy system and the dynamic complexities of the energy transition.

Table 8. Causal and Interrelationship between Different Modelling Variables.

Source	Target	Type *	Delay †	*Cause*	VALIDATING References ‡
Regional Renewable Energy Production	Renewable Energy Technology Proficiency	+	Y	*Renewable Energy Technology Maturity*	[14,51,52,58]
Renewable Energy Technology Proficiency	Costs of Investment in Renewable Energy Technology	-		*High Degree of Technology Adoption*	[14,16,51,52,58,70]
Costs of Investment in Renewable Energy Technology	Attractiveness of Renewable Energy Technology	-		*Affordability of Technology*	[51,58]
Attractiveness of Renewable Energy Technology	Investment in Renewable Energy Technology	+		*Decision on Investment in Energy Technologies*	[14,51,58]
Investment in Renewable Energy Technology	Regional Renewable Energy Production	+	Y	*Impact on Energy Production Capacity*	[5,24,28,51,58,60,61,69,70,76,77]
Regional Renewable Energy Production	GHG Emission	-		*Emission Associated with Energy Production and Distribution*	[6,28,30,42,49,51,58,76]
Regional Renewable Energy Production	Energy Costs	+		*Cost of producing one unit of renewable energy*	[17,20,28,51,61,69]
Regional Fossil Fuel Energy Production	Fossil Fuel Energy Technology Proficiency	+	Y	*Renewable Energy Technology Maturity*	[14,51,52,58]
Fossil Fuel Energy Technology Proficiency	Costs of Investment in Fossil Fuel Energy Technology	-		*High Degree of Technology Adoption*	[14,16,51,52,58,70]
Costs of Investment in Fossil Fuel Energy Technology	Attractiveness of Fossil Fuel Energy Technology	-		*Affordability of Technology*	[51,58]
Attractiveness of Fossil Fuel Energy Technology	Investment in Fossil Fuel Energy Technology	+		*Decision on Investment Energy Technologies*	[14,51,58]
Investment in Fossil Fuel Energy Technology	Regional Fossil Fuel Energy Production	+	Y	*Impact on Energy Production Capacity*	[5,24,28,51,58,60,61,69,70,76,77]
Regional Fossil Fuel Energy Production	GHG Emission	+		*Emission Associated with Energy Production and Distribution*	[6,28,30,42,49,51,58,76]
Regional Fossil Fuel Energy Production	Energy Costs	+		*Cost of producing one unit of energy Fossil Fuel*	[17,20,28,51,61,69]
Energy Demand	Investment in Renewable Energy Technology	+		*Pressure to Invest in Energy Technology*	[14,17,48,49,51,76]
Energy Demand	Investment in Fossil Fuel Energy Technology	+		*Pressure to Invest in Energy Technology*	[14,17,42,48,49,51,76]
Regional Fossil Fuel Energy Production	Energy Demand	-		*Energy Supply from Fossil Fuels*	[15,17,30,42,46,50,51,60,61,77]
Regional Renewable Energy Production	Energy Demand	-		*Energy Supply from Renewables*	[15,17,30,42,46,50,51,60,61,77]
Industrial Activities	Energy Demand	+		*Energy Demand Associated with Industrial Activities*	[14,15,17,42,56,60,61]
Population	Energy Demand	+		*Energy Demand Associated with the Population*	[6,14–17,24,28,30,42,50,52,56,74]
Energy Price	Energy Demand	-		*Impact of Energy Price on Energy Demand*	
Investment in Renewable Energy Technology	Employment	+		*Job Creation Associated with Energy Infrastructure Development*	[9,13]
Investment in Fossil Fuel Energy Technology	Employment	+		*Job Creation Associated with Energy Infrastructure Development*	[9,13]
GHG Emission	Climate Change	+	Y	*Concentration of Greenhouse Gases*	[19,23,24,51,58]
GHG Emission	Population	-	Y	*Negative Impact of GHG Pollution on Public Health*	[9,19,23,76]
Climate Change	GDP	-	Y	*Economic impact of GHG emission*	[23]
Climate Change	Policies for Climate Change Mitigation	+		*Urgency of Climate Change Mitigation*	[42,46,51,58]
Policies for Climate Change Mitigation	Attractiveness of Renewable Energy Technology	+		*Subsidies for Renewable Energy Investments*	[14,42,46,51,58]
Policies for Climate Change Mitigation	Attractiveness of Fossil Fuel Energy Technology	-		*Cause of Fossil Fuel Phase Out Policies*	[14,42,46,51,58]
GDP	Attractiveness for Industry to come to Tees Valley	+		*Economic Incentives for Businesses to come to Tees Valley*	[14,23]
Energy Costs	GDP	-		*Economic Costs of Energy Production*	[17,20,48,51,60]
Industrial Activities	GDP	+		*Tax Income from Industrial Activities*	
Employment	GDP	+		*Salary Tax Income*	[40]
Employment	Population	+		*People Seeking Employment*	[13,24,56]
Industrial Activities	Employment	+		*Job Creation Associated with Industrial Activities*	[9,13,56]
Industrial Activities	GHG Emission	+		*GHG Emissions Associated with industrial Activities*	[25,33,42,49,74]
Population	Population Change	-		*Person Dies*	[19,25,34,56,62,63,74,76]
Population Change	Population	+		*Person Born*	[19,25,34,56,62,63,74,76]
Energy Costs	Energy Price	+		*Price Change Associated with Energy Costs*	[20,28,61]
Attractiveness for Industries to come to Tees Valley	Industrial Activities	+		*New Companies coming to Tees Valley Region*	[58]
Population	GHG Emission	+		*GHG Emission Associated with Population*	[11,34,42,49]
Investment in Renewable Energy Technology	Attractiveness for Industries to come to Tees Valley	+		*New Opportunity to Attract Businesses to come to Tees Valley*	[58]

* (+) Positive Causal Relationship and (–) Negative Causal Relationship. † Delay timeframe 5 years longer. ‡ (See Table A1 in Appendix A for Paper IDs).

4.5. Challenges and Complexity

This section focuses on discussing the major challenges policymakers are facing in relation to energy transition in the context of the Tees Valley energy system.

4.5.1. Technological Dependency

The energy transition is a highly technology-dependent problem since it requires a restructuring and re-designing of the conventional fossil fuel-based energy system, which has been the primary energy system since the industrial revolution [1,2]. This restructuring focuses on bringing more RET into the energy portfolio. This can be, for example, geothermal, hydropower, solar energy, or wind energy based on various factors such as technological proficiency, geographical location, and access to and stability of these RES [12,50,121,128]. Furthermore, energy transition is a focal problem that society is trying to solve since it plays a crucial part in the mitigation of climate change, given the fact that energy accounts for close to three-quarters of global GHG emissions [11,13,17]. Thus, energy transition towards a decarbonised energy system is driven by policies that push for the implementation of renewable energy technologies for climate change mitigation [2,5,7–9,11,13,17,78]. The bolded lines in the CLD shown in Figure 11 above highlight the aspects that build the technological know-how for being more efficient in the technological implementation alongside the policy drive for increasing renewables.

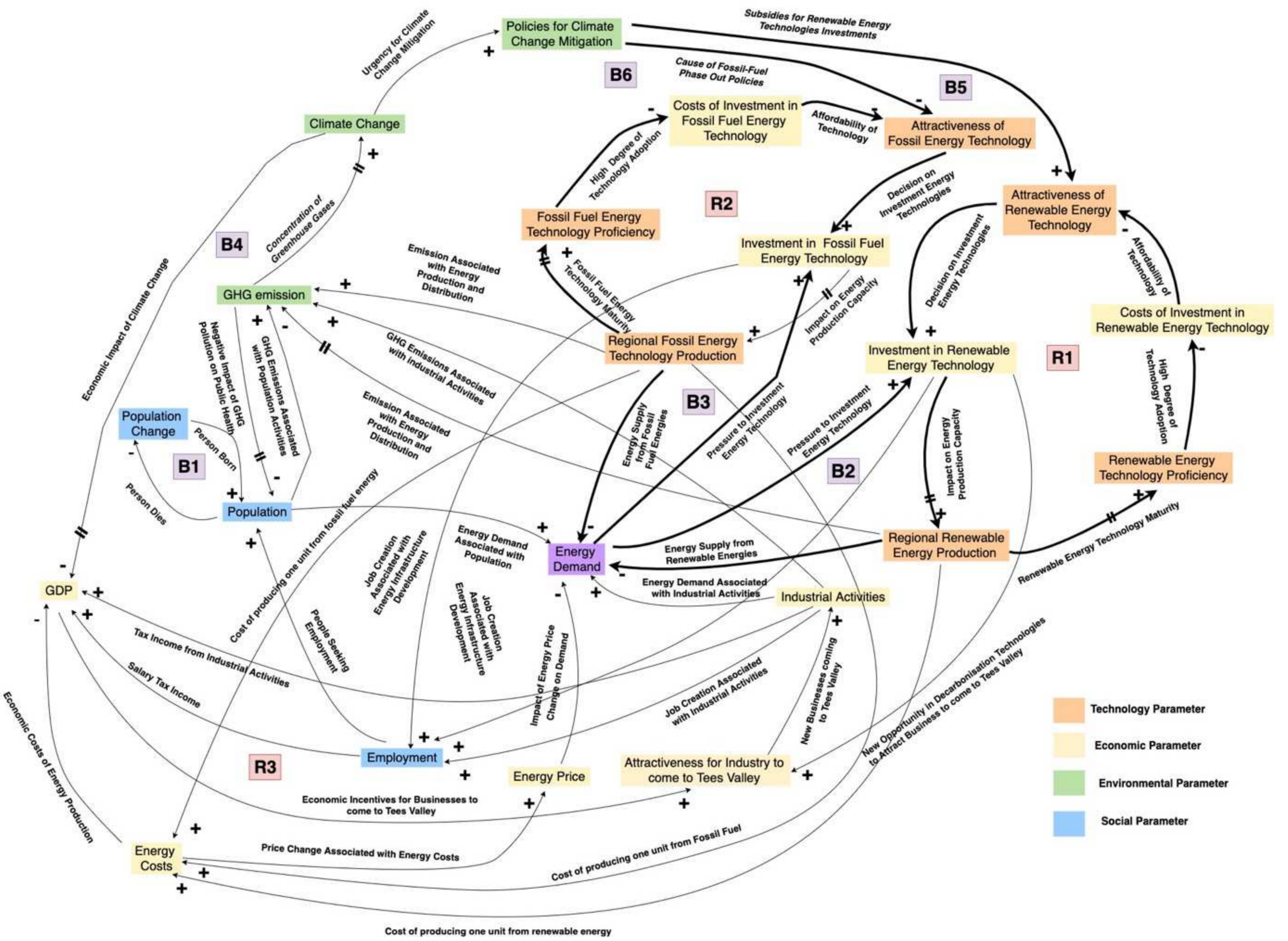

Figure 11. Qualitative based Causal Loop Diagram of Tees Valley Energy System, **Highlighted Line** depicts the interlinking relationship concerning the Technological Dependency and Energy Policy Design.

The selection of feasible renewable energy sources has to be based on geographical location to foster the energy transition. Based on the current energy portfolio, Tees Valley has offshore wind and bioenergy within its regional energy system. This indicates a level of technological know-how and infrastructure readiness to increase the capacities of these two energy technologies and, therefore, provide a foundation for these technologies to be considered as the core technologies for Tees Valley's energy transition. Since these technologies are already an established part of the energy system, the complexity that can arise from factors such as construction time and investment costs decrease, and the ability to overcome any related challenges increases. As the energy system infrastructure in the region is accustomed to these technologies already, the need to upgrade the energy transmission and distribution networks to accompany new energy technologies are mitigated alongside avoiding technology-linked threats to energy security due to a decrease in energy stability.

4.5.2. Social Prosperity

For the Tees Valley region, improving and establishing a good living standard is a crucial element that needs to be achieved through any energy transition policy. As pointed out in the case study section, the Tees Valley region is considered a highly deprived area and is ranked high when it comes UK national deprivation scale [30–33]. Thus, one to emphasise for policymakers in the Tees Valley region is that energy transition and energy system development policies proposed to lead to a growth in job opportunities for the local workforce alongside attracting new and skilled workers to the region [30–33]. Reference [129] highlighted that implementation of the right policies and technologies could create more job opportunities and decrease potential job losses associated with the energy transition. Meanwhile, poorly formed and mismanaged policies cause negative impacts on employment through either job losses or lack of jobs created, which negatively affects the economic opportunities that the energy transition can create for the region. Reference [99] emphasised the ability of infrastructure development to impact employment through increased job creation caused by policy choices that foster infrastructure development. Reference [49] pointed out that new technology implementation is associated with employment creation. This is relevant to the energy transition since it entails the introduction and implementation of new technologies. It is highlighted that the early stages of energy technology integration offer a lot of job opportunities, whereas increased jobs opportunities could be limited due to a lack of employee turnovers, a saturation of the employment market, and a halt in investments in technology and energy production capacity growth. Reference [49] emphasised that correct policies combined with support for technological development can increase employment opportunities and the quality of employment, which can, in turn, improve the social and public welfare of a region. All these papers highlight and emphasise that energy transition policies need to be developed and implemented through a just and meticulous process to ensure quality employment opportunities. In the case of Tees Valley, emphasis on ensuring employment growth and avoiding unemployment creation in the region can lead to a dilemma in terms of the energy transition, which has the prominent objective of pushing for decarbonisation and phasing out of fossil fuel energy sources. This makes it even more important that the Tees Valley policies encompass the right choice in technological development and investments, which allows for employees of fossil fuel energy production facilities to transit easily to and gain employment in the renewable energy field. The bolded lines in Figure 12 highlight the aspects of employment through investment in RES as part of the energy transition and system development.

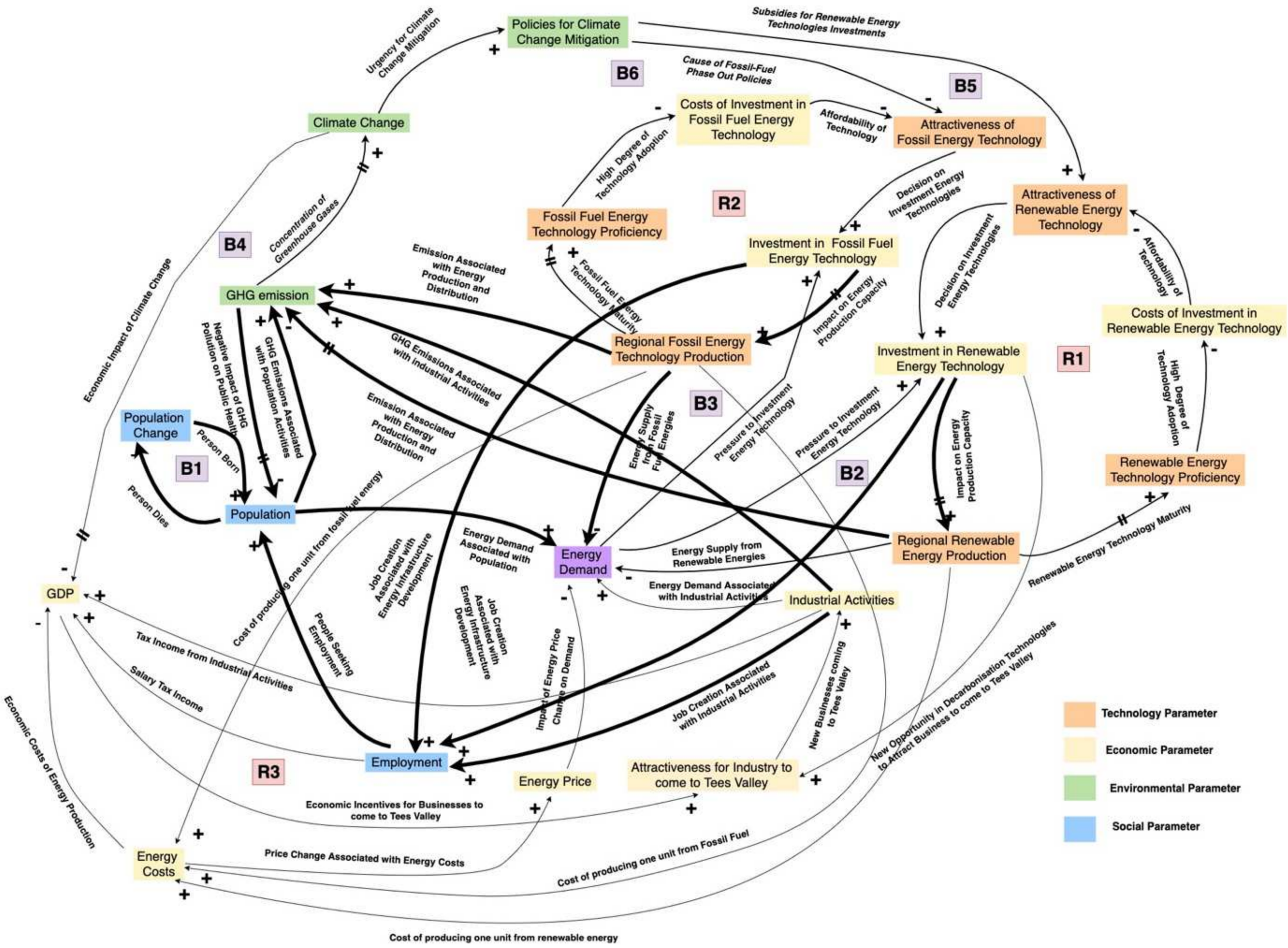

Figure 12. Qualitative based Causal Loop Diagram of Tees Valley Energy System, **Highlighted Line** depict the interlinking relationship concerning Social Prosperity and Energy Policy Design.

5. Limitations and Future Work

As with other review and semi-empirical based studies, this study also has its clear limitations. The model presented in this paper is based on insights gained from researching the literature and then tailored to the case study area based on the researchers' knowledge and also discussion with senior academics in the field of energy systems, energy transition, and energy policies. Future research will use a survey with experts for further validation of the feedback loops, dynamics, and interlinkages presented in this paper, to further enhance the reliability of the results and be able to achieve replicability and roll out to support and help in net-zero policy design in the region across other industrial clusters. Another limitation pertains to the keywords for the Boolean search in the extensive structure review process since some may consider that other keywords should be selected and used to ensure more papers are identified and analysed. The keywords selection for the extensive structure review process in this paper was based on the research topic, review of other papers relevant to the topic, and discussion with academics both within and outside the research team. This was performed to ensure that the keywords selected were fit for the problem being investigated. It is important to keep in mind that this kind of research involving the Tees Valley Region, assessing the energy transition and energy system development policies, has not been carried out before. Therefore, the results presented in this paper provide the vital groundwork for the work ahead.

6. Conclusions

By applying a two-phase research process using the extensive structure literature review approach, in combination with a system dynamic methodology, this paper highlights the complexity of energy transition policymaking. Firstly, the presentation of a real-world case study illustrates that energy system transition represents a multi-dimensional and highly complex system, exposing a vast volume of modeling variables and dynamic relationship structures that intertwine and connect the three traditional sustainability dimensions. Secondly, this work emphasises the technological interdependency of the energy transition while underscoring that energy transition policies need to consider all relevant social, economic, environmental, and technological aspects to be successful. Thirdly, the paper illustrates that when looking at energy transition policymaking, considering technology as the fourth core dimension—in combination with the three traditional sustainability dimensions—is not only recognised within the research community but brings associated benefits. Fourthly, through the development and construction of a qualitative causal loop diagram based upon the introduced real-world case study, the possibility to provide a high-level overview of a regional energy system's complexity is illustrated, along with the challenging conditions policymaking is confronted with when designing and developing policies. The application of the approach presented in this paper provides insights into variables, such as populations, employment, energy production capacity of respective energy technologies in the system, energy demand, greenhouse gas emission, and investment in energy technology, that are significant to be included in policy design support tool in relation to the energy transition. In addition, in order to provide insight into the interconnective and causal–effect relationship between variables such as investments in technologies and climate change mitigation, energy system development, employment, and attracting new businesses to the region and population. Therefore, providing the policymakers with an illustrative map that has the ability to highlight the dynamic relationship and causality between different crucial variables and different policy pathways associated with energy transition policymaking, hence enhancing the knowledge base within local governmental policy mechanisms on the potential impacts and effects energy system development and climate change mitigation policies have on the society. Finally, this paper highlights the strength and effectiveness of utilising a systematic literature review approach combined with an illustrative modelling approach such as system dynamics to generate an in-depth understanding of problems as complex as the energy transition in the context of a specific region or city. Indeed, this approach can be replicated across net-zero policy design for other industrial clusters. Based on the findings and information presented in this paper, the policymakers in Tees Valley face challenges in ensuring that any policy developed for the energy transition and energy system development needs to emphasise social growth and enable improvements in living standards through increased job opportunities, better quality jobs while avoiding job losses related to the energy transition.

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Abbreviations

RES	Renewable Energy Resources
IPCC	The United Nations Intergovernmental Panel on Climate Change
RET	Renewable Energy Technology
UN SDGs	the United Nations Sustainable Development Goals
CLD	Causal Loop Diagram
PRISMA	Systematic Reviews and Meta-Analyses
UK	United Kingdom
TVCA	the Tees Valley Combined Authorities

Appendix A

Appendix A.1. Structure Literature Review Information

In this study, 106 papers published between 2000 and early 2021 were selected using the systematic review approach for the purposes of (i) gaining an understanding of the application methods used in the papers in terms of integration of system dynamics methodology with sustainability assessment; (ii) gaining insights into the dimensions included in modelling within the context of energy transition and complex problems, to further understand if technology can be considered as a fourth dimension; and (iii) gaining an understanding of the volume of modelling variables included in system dynamic models when looking at multi-layered and complex problems.

Figure A1 illustrates the distribution of published papers over the selected timeframe. Most of the papers selected for this analysis were published between 2018 and 2020, and the earliest paper used in the analysis was published in 2003.

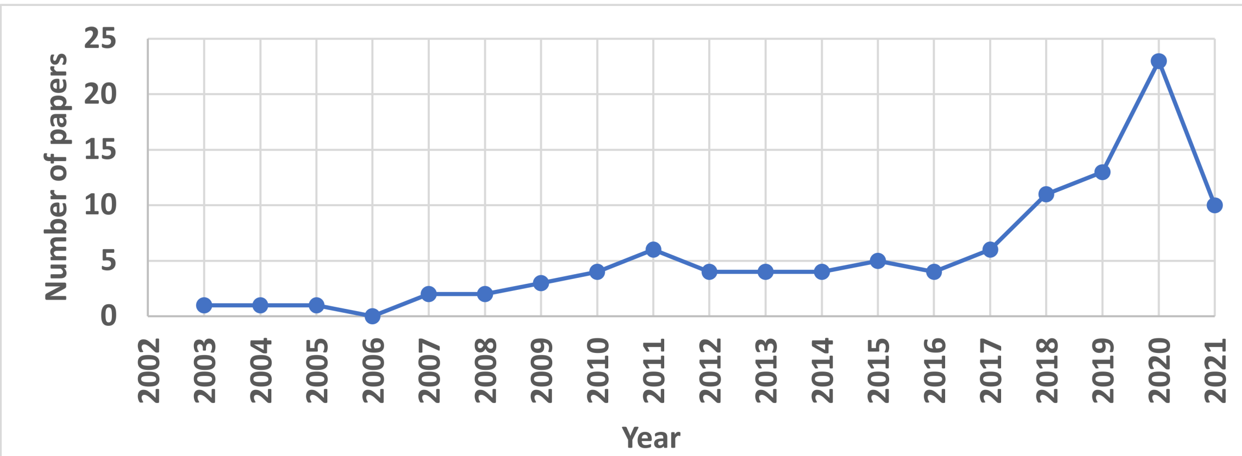

Figure A1. Number of Publications per year.

As shown in Figure A2, the largest numbers of publications come from three journals: The Journal of Cleaner Production, Environmental Impact Assessment Review, and Sustainability.

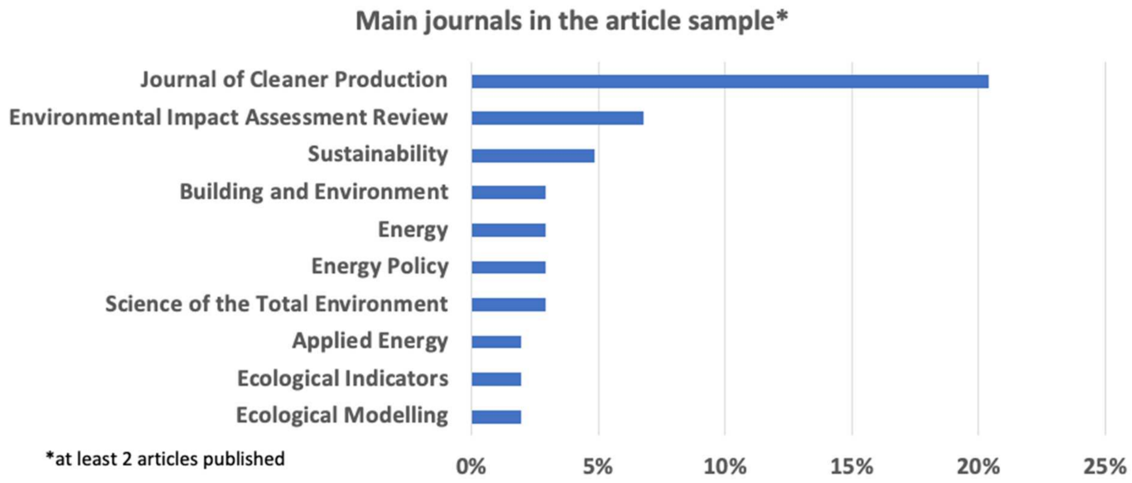

Figure A2. Order of key journal based on article reviewed.

As indicated in Figure A3, roughly 75% of the papers selected involve research conducted using system dynamics approaches. The first step in the systematic review analysis was looking at the application of system dynamics and sustainability assessment as an integrated approach across the selected papers. As can be seen in Figure A3, 13% of the 106 reviewed papers utilised a system dynamic method integrated with sustainability assessment, where large volume of reviewed paper or 62% utilize system dynamic as the main method.

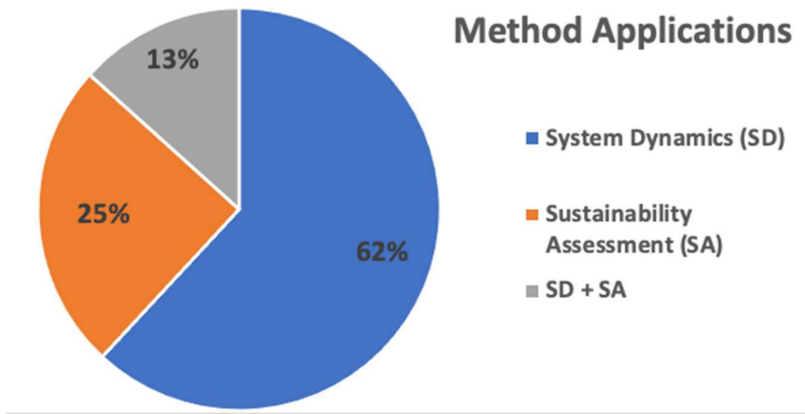

Figure A3. Division of Method Application.

Appendix A.2. Content and Paper Analysis Framework

Table A1. Content Analysis Framework.

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
1	A system dynamics model for CO_2 mitigation strategies at a container seaport	Y. Mamatok, Y.Huang, C. Jin et al.	2019	Sustainability (Switzerland)	Ii	x			x		x
2	Strategic policy analysis for infrastructure rehabilitation using system dynamics	R. Rashedi and T. Hegazy	2016	Structure and Infrastructure Engineering	I	x		x	x	x	x
3	Rethinking urban sustainability using fuzzy cognitive mapping and system dynamics	E. R. G. T. R. Assunção, F. A. F. Ferreira, I. Meidutė-Kavaliauskienė, C. Zopounidis, L. F. Pereira and R. J. C. Correia	2020	International Journal of Sustainable Development and World Ecology	S	x		x	x	x	
4	Sustainability Assessment of Asset Management Decisions for Wastewater Infrastructure Systems—Implementation of a System Dynamics Model	Hamed Mohammadifardi, Mark A. Knight, and Andre A. J. Unger	2019	Systems	S, I	x	x	x	x		x
5	Towards Decision-Making for the Assessment and Prioritization of Green Projects: An Integration between System Dynamics and Participatory Modeling	Gerard Olivar-Tost, Johnny Valencia-Calvo and Julián Andrés Castrillón-Gómez	2020	Sustainability (Switzerland)	S	x		x	x	x	
6	A system dynamics model for simulating the logistics demand dynamics of metropolitans: A case study of Beijing, China	Qiu, Ying; Shi, Xianliang; Shi, Chunhua	2015	Journal of Industrial Engineering and Management (JIEM)		x		x	x	x	x
7	Mapping Maritime Sustainability Issues with Stakeholder Groups	Nuno Videira et al.	2012	Systems Research and Behavioral Science	S	x			x	x	
8	Eco-cities: An integrated system dynamics framework and a concise research taxonomy	N. Tsolakis, L. Anthopoulos	2015	Sustainable Cities and Society		x		x	x	x	x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
9	Sustainability assessment of the tanjung priok port cluster	Moeis et al.	2020	International Journal of Technology	S, I	x	x	x	x	x	
10	Integrating life cycle analysis into system dynamics: the case of steel in Europe	Julian T. M. Pinto, Harald U. Sverdrup and Arnaud Diemer	2019	Environmental Systems Research		x		x	x		
11	Application of System Dynamics model and GIS in sustainability assessment of urban residential development	Zhao Xu	2011	International Journal of Applied Earth Observation and Geoinformation	S, I	x	x	x	x	x	
12	Modeling social sustainability in construction projects by integrating system dynamics and fuzzy-DEMATEL method: a case study of highway project	Mozhdeh Rostamnezhad and Farnad Nasirzadeh, Mostafa Khanzadi, Mohammad Jafar Jarban, Masoud Ghayoumian	2020	Engineering, Construction, and Architectural Management	S, I	x				x	
13	A system dynamics model and analytic network process: An integrated approach to investigate urban resilience	Marta Bottero, Giulia Datola and Elena De Angelis	2020	Land		x		x	x	x	
14	Systems dynamics modelling to assess the sustainability of renewable energy technologies in developing countries	A. C. Brent, M. B. Mokheseng, B. Amigun, H. Tazvinga, and J. K. Musango	2011	WIT Transactions on Ecology and the Environment		x		x		x	x
15	System Dynamics Urban Sustainability Model for Puerto Aura in Puebla, Mexico	Jorge A. Duran-Encalada, Alberto Paucar-Caceres	2009	Systemic Practice and Action Research	S	x		x	x	x	
16	Developing a sustainability assessment framework for integrated management of water resources systems using distributed zoning and system dynamics approaches	Mehri Abdi-Dehkordi, Omid Bozorg-Haddad, Abdolrahim Salavitabar, Erfan Goharian	2021	Environment, Development, and Sustainability	I, S	x	x	x			x
17	System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach	Mohammad Javad Keyhanpour, Seyed Habib Musavi Jahromi, and H. Ebrahimi	2021	Ain Shams Engineering Journal	S, I, E	x		x	x	x	x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
18	A conceptual framework for energy technology sustainability assessment	J.K. Musango, A.C. Brent	2011	Energy for Sustainable Development	E, S	x	x	x	x	x	x
19	A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact	G. Egilmez, O. Tatari	2012	Transportation Research Part A: Policy and Practice	S, I	x		x	x		x
20	A system dynamics approach for sustainability assessment of biodiesel production in Colombia. Baseline simulation	S. Bautista et al.	2019	Journal of Cleaner Production	S, E, I	x	x	x	x	x	x
21	Challenges Facing South Africa's Electricity Sector's Integrated Resource Plan—A Qualitative System Dynamics Approach	L Mqadi, J K Musango, A C Brent	2018	Administratio Publica	E	x					
22	Testing and verification of a new corporate sustainability assessment method for manufacturing: A multiple case research study	Moldavska, Anastasiia, Welo, Torgeir	2018	Sustainability (Switzerland)	I	x	x	x			
23	Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles	Nuri C. Onat and Murat Kucukvar and Omer Tatari and Gokhan Egilmez	2016	International Journal of LIFE CYCLE ASSESSMENT	S, E, I	x	x	x	x	x	
24	A system dynamics based simulation model to evaluate regulatory policies for sustainable transportation planning	Reza Sayyadi and Anjali Awasthi	2017	International Journal of Modelling and Simulation		x		x	x	x	
25	A system dynamics model for simulating urban sustainability performance: A China case study	Yongtao Tan, Liudan Jiao, Chenyang Shuai, Liyin Shen	2018	Journal of Cleaner Production journal		x		x	x	x	x
26	System dynamics model of a biotechonomy.	Blumberga, A., Bazbauers, G., Davidsen, P. I., Blumberga, D., Gravelsins, A., and Prodanuks, T.	2018	Journal of Cleaner Production		x		x			x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
27	Sustainability assessment of last-mile logistics and distribution strategies: The case of local food networks	A. Melkonyan et al.	2020	International Journal of Production Economics		x		x	x		
28	Technology sustainability assessment of biodiesel development in South Africa: A system dynamics approach	J.K. Musango et al.	2011	Energy		x		x	x	x	x
29	Towards greening the U.S. residential building stock: A system dynamics approach	N.C. Onat et al.	2014	Building and Environment		x		x		x	
30	System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia	Sušnik, J., Masia, S., Indriksone, D., Brēmere, I., and Vamvakeridou-Lydroudia, L.	2021	Science of the Total Environment		x		x	x	x	
31	Developing a Model for Sustainability Assessment in LARG Supply Chains using System Dynamics	M. Izadyar et al.	2021	Int. J. Industrial Mathematics	S, I	x	x	x			
32	Application of system dynamics modelling in evaluating sustainability of low-input ruminant farming systems in Eastern Cape Province, South Africa	T. Marandure, et al.	2020	Ecological Modelling		x		x	x	x	
33	Using system dynamics to assess the environmental management of cement industry in streaming data context	E. Ekinci et al.	2020	Science of the Total Environment journal		x		x	x	x	
34	System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran	Z. Ravar, et al.	2020	Ecological Indicators		x			x	x	x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
35	Engaging stakeholders in the assessment ofNBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation	A. Pagano et al.	2019	Science of the Total Environment		x		x	x	x	
36	Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development	Z. Xu, V. Coors	2012	Building and Environment journal		x		x	x	x	
37	Development of a system dynamics model for sustainable land use management	Chien-Hwa Yu, Ching-Ho Chen, Cheng-Fang Lin and Shiu-Liang Liaw	2003	Journal of the Chinese Institute of Engineers	S, I	x	x	x	x		
38	Water resources planning based on complex system dynamics: A case study of Tianjin city	X.H. Zhang et al.	2008	Communications in Nonlinear Science and Numerical Simulation		x			x	x	
39	A Participatory Modelling Approach to Support Integrated Sustainability Assessment Processes	Nuno Videira, Paula Antunes, Rui Santos and Rita Lopes	2010	Systems Research and Behavioral Science	S	x	x				
40	Modeling and dynamic assessment of urban economy-resource-environment system with a coupled system dynamicsGeographic information system model	D. Guan et al.	2011	Ecological Indicators	S, I	x	x	x	x	x	x
41	A system dynamics approach to technology sustainability assessment: The case of biodiesel developments in South Africa	J.K Musango et al.	2012	Technovation journal		x		x	x	x	
42	A Systemic Conceptual Model to Support Decision-Making in the Sustainability Assessment of Industrial Ecosystems	Dulce Rocío Mota-López, Cuauhtémoc Sánchez-Ramírez, Giner Alor-Hernández, et al. The	2017	Research in Computing Science		x			x	x	x
43	Using system dynamics to evaluate renewable electricity development in Malaysia	Salman Ahmad and Razman bin Mat Tahar	2014	Kybernetes		x					x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
44	Sustainable development analysis of design and manufacturing integration: A system dynamics approach	Liyuan Liu, Yen Hsu and Jialiang Lin	2019	Cogent Engineering		x		x	x	x	x
45	Sustainable site selection using system dynamics; case study LEED-certified project	Walaa S.E. Ismaeel	2021	Architectural Engineering and Design Management		x			x	x	x
46	Low-Carbon Energy Governance: Scenarios to Accelerate the Change in the Energy Matrix in Ecuador	Flavio R. Arroyo M. and Luis J. Miguel	2020	Energies	E	x		x	x		
47	Macroeconomic modelling under energy constraints: Global low carbon transition scenarios	J. Nieto et al.	2020	Energy Policy	E	x		x		x	
48	Substitution Effect of Natural Gas and the Energy Consumption Structure Transition in China	Weiwei Xiong, Liang Yan, Teng Wang and Yuguo Gao	2020	Sustainability (Switzerland)	E	x		X			X
49	The limits of transport decarbonization under the current growth paradigm	I. de Blas et al.	2020	Energy Strategy Reviews	E	x		x	x		
50	When justice narratives meet energy system models: Exploring energy sufficiency, sustainability, and universal access in Sub-Saharan Africa	G. Gladkykh et al.	2021	Energy Research and Social Science	E, S	x				x	x
51	The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?	C. Gürsan and V. de Gooyert	2021	Renewable and Sustainable Energy Reviews		x		x	x		x
52	Investigating the sustainability of a food system by system dynamics approach	Amiri, A., Mehrjerdi, Y. Z., Jalalimanesh, A., and Sadegheih, A	2020	Journal of Cleaner Production	S,I	x	x		x	x	x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
53	Integrated Agent-based and System Dynamics Modelling for Simulation of Sustainable Mobility	Ehsan Shafiei, Hlynur Stefansson, Eyjolfur Ingi Asgeirsson, Brynhildur Davidsdottir and Marco Raberto	2013	Transport Reviews	E, I	x		x	x		x
54	System dynamics simulation for CO_2 emission mitigation in green electric-coal supply chain	Cao, Y., Zhao, Y., Wen, L., Li, Y., Li, H., Wang, S., Liu, Y., Shi, Q., and Weng, J	2019	Journal of Cleaner Production	E, I	x		x	x		x
56	Participatory system dynamics modelling for housing, energy and wellbeing interactions	Eker, S., Zimmermann, N., Carnohan, S., and Davies, M	2018	Building Research and Information	I	x		x		x	x
57	System dynamics modeling for urban energy consumption and CO_2 emissions: A case study of Beijing, China	Feng, Y. Y., Chen, S. Q., and Zhang, L. X	2013	Ecological Modelling	E, S, I	x		x	x	x	x
58	Policy analysis of the Jakarta carbon mitigation plan using system dynamics to support decision making in urban development—options for policymakers	Hidayatno, A., Rahman, I., and Muliadi, R.	2015	International Journal of Technology	E, S, I	x		x	x	x	x
59	Understanding contrasting narratives on carbon dioxide capture and storage for Dutch industry using system dynamics	Janipour, Z., Swennenhuis, F., de Gooyert, V., and de Coninck, H	2021	International Journal of Greenhouse Gas Control	E, S, I	x			x	x	x
60	A system dynamics analysis of the alternative roofing market and its potential impacts on urban environmental problems: A case study in Orlando, Florida	Kelly, C., Sen, B., and Tatari, O.	2020	Resources, Conservation and Recycling	E, I	x			x		x
61	A system dynamic model for production and consumption policy in Iran oil and gas sector	Kiani, B., and Ali Pourfakhraei, M	2010	Energy Policy	E, I	x		x			x
62	A Survey on the Role of System Dynamics Methodology on Fossil Fuel Resources Analysis	Kiani, Behdad and Saeed, Mirzamohammadi and Hosseini, Seyed Hossein.	2010	International Business Research	E	x		X			X

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
63	System dynamics modelling for improving urban resilience in Beijing, China	Li, G., Kou, C., Wang, Y., and Yang, H.	2020	Resources, Conservation and Recycling	E, S, I	x		x	x	x	x
64	Operationalizing sustainability in urban coastal systems: A system dynamics analysis	Mavrommati, G., Bithas, K., and Panayiotidis, P.	2013	Water Research	S	x		x	x	x	
65	A model for the complexity of household energy consumption	Motawa, I., and Oladokun, M.	2015	Energy and Buildings,	E, I	x		x	x	x	x
66	Applying backcasting and system dynamics towards sustainable development: The housing planning case for low-income citizens in Brazil.	Musse, J. de O., Homrich, A. S., de Mello, R., and Carvalho, M. M.	2018	Journal of Cleaner Production	I	x		x		x	
67	Systems thinking for life cycle sustainability assessment: A review of recent developments, applications, and future perspectives	Onat, N. C., Kucukvar, M., Halog, A., and Cloutier, S.	2018	Sustainability	E, S, I	x	x	x	x	x	
68	A system dynamics model of socio-technical regime transitions	Papachristos, G.	2011	Environmental Innovation and Societal Transitions		x		x		x	x
69	System dynamics models for the simulation of sustainable urban development: A review and analysis and the stakeholder perspective	Pejic Bach, M., Tustanovski, E., Ip, A. W. H., Yung, K. L., and Roblek, V.	2019	Kybernetes	E, S, I	x		x	x	x	
70	Analysis of supply-push strategies governing the transition to biofuel vehicles in a market-oriented renewable energy system	Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., Asgeirsson, E. I., and Keith, D. R.	2016	Energy	E, I	x		x			x
71	Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach	Shih, Y. H., and Tseng, C. H.	2014	Applied Energy	E, I	x		x			x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
72	The role of geothermal resources in sustainable power system planning in Iceland	Spittler, N., Davidsdottir, B., Shafiei, E., Leaver, J., Asgeirsson, E. I., and Stefansson, H	2020	Renewable Energy	E, I	x		x			x
73	Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs	Spittler, N., Shafiei, E., Davidsdottir, B., and Juliusson, E.	2020	Energy	E, I	x		x			x
74	A system dynamics modeling for urban air pollution: A case study of Tehran, Iran	Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., and Moazen, S.	2014	Transportation Research Part D: Transport and Environment	E, S, I	x		x	x	x	x
75	A study of regional sustainable development based on GIS/RS and SD model—Case of Hadaqi industrial corridor	Wan, L., Zhang, Y., Qi, S., Li, H., Chen, X., and Zang, S.	2017	Journal of Cleaner Production	S	x		x	x	x	
76	Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing	Wu, D., and Ning, S.	2018	Environmental Research	E, S, I	x		x	x	x	x
77	Dynamics of the North-South welfare gap and global sustainability	Yücel, G., and Barlas, Y.	2010	Technological Forecasting and Social Change	E, S, I	x		x	x	x	x
78	Clean and secure power supply: A system dynamics based appraisal	Zapata, S., Castaneda, M., Franco, C. J., and Dyner, I.	2019	Energy Policy	E	x		x			x
79	Developing a generic System Dynamics model for building stock transformation towards energy efficiency and low-carbon development	Zhou, W., Moncaster, A., Reiner, D. M., and Guthrie, P	2020	Energy and Buildings	I	x					x
80	Toward the dynamic modeling of transition problems: The case of electric mobility	Zolfagharian, M., Walrave, B., Romme, A. G. L., and Raven, R.	2021	Sustainability	I	x					x
81	Integrated assessment for sustainability appraisal in cities and regions	Joe Ravetz	1999	Environmental Impact Assessment Review	E, S, I		x	x	x	x	

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
82	Evaluation of coastal zone sustainability: an integrated approach applied in Shanghai Municipality and Chong Ming Island	C, Shi, S.M. Hutchinson, S, Xu	2004	Journal of Environmental Management	S, I		x	x	x	x	
83	Sustainability indices as a tool for urban managers, evidence from four medium-sized Chinese cities	M.P. van Dijk, Z. Mingshun	2005	Environmental Impact Assessment Review	S		x	x	x	x	
84	Sustainability index for Taipei	Yung-Jaan Lee, Ching-Ming Huang	2007	Environmental Impact Assessment Review	S		x	x	x	x	
85	Key performance indicators and assessment methods for infrastructure sustainability—a South African construction industry perspective	O.O. Ugwu, T.C. Haupt	2007	Building and Environment	S, I		x	x	x	x	x
86	Practical appraisal of sustainable development—Methodologies for sustainability measurement at settlement level	Richard Moles, Walter Foley, John Morrissey, Bernadette O'Regan	2008	Environmental Impact Assessment Review	S,I		x	x	x	x	
87	A Sensitivity Model (SM) approach to analyze urban development in Taiwan based on sustainability indicators	S.-L. Huang et al.	2009	Environmental Impact Assessment Review	E, S, I		x	x	x	x	
88	An alternative model for measuring the sustainability of urban regeneration: the way forward	Yi Peng, Yani Lai, Xuewen Li, Xiaoling Zhang d	2015	Journal of Cleaner Production	S, I		X	x	x	x	
89	An innovative sustainability assessment for urban wastewater infrastructure and its application in Chengdu, China	A. Murray et al.	2009	Journal of Environmental Management	S, I		X	x	x	x	x

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
90	A contribution to the structural model of autonomous sustainable neighbourhoods: new socio-economical basis for sustainable urban planning	Primoz Medved	2016	Journal of Cleaner Production	S, I		X	x	x	x	
91	A decision-support system for sustainable urban metabolism in Europe	A. González et al.	2013	Environmental Impact Assessment Review	S		X	x	x	x	
92	Measuring sustainability at the community level: An overview of China's indicator system on National Demonstration Sustainable Communities	Yangsiyu Lu, Yong Geng, Zhe Liu, Raymond Cote, Xiaoman Yu	2017	Journal of Cleaner Production	S, I		X	x	x	x	
93	A holistic low carbon city indicator framework for sustainable development	Sieting Tan, Jin Yang, Jinyue Yan, Chewtin Lee, Haslenda Hashim, Bin Chen	2017	Applied Energy	S, E, I		X	x	x	x	
94	Comprehensive evaluation of different scale cities' sustainable development for economy, society, and ecological infrastructure in China	Xiao Sun, Xusheng Liu, Feng Li, Yu Tao, Yingshi Song	2017	Journal of Cleaner Production	E, S, I		X	x	x	x	
95	Sustainability assessment and key factors identification of first-tier cities in China	P. Yi, W. Li, and D. Zhang	2021	Journal of Cleaner Production	S		X	x	x	x	
96	Evaluating the sustainability of marine industrial parks based on the DPSIR framework	Xu Liu, Huatai Liu, Jichun Chen, Tengwei Liu, Zelin Deng	2018	Journal of Cleaner Production	S, I		X	x	x	x	
97	A participatory sustainability assessment for integrated watershed management in urban China	Daniele Brombal, Yuan Niu, Lisa Pizzol, Angela Moriggi, Jingzhi Wang, Andrea Critto, Xia Jiang, Beibei Liu, Antonio Marcomini	2018	Environmental Science and Policy	S, I		X	x	x	x	

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
98	A system dynamics model for simulating urban sustainability performance: A China case study	Yongtao Tan, Liudan Jiao, Chenyang Shuai, Liyin Shen	2018	Journal of Cleaner Production	S, E, I		X	x	x	x	
99	Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain)	Sara Gonz?alez-García, Manuel Rama, Antonio Cort?es, Fernando García-Guaita, Andr?es Nú~nez, Lucía Gonz?alez Louro, Maria Teresa Moreira, Gumersindo Feijoo	2019	Journal of Cleaner Production	S		x	x	x	x	
100	Evaluating water resource sustainability in Beijing, China: Combining PSR model and matter-element extension method	Qiang Wang, Siqi Li, Rongrong Li	2019	Journal of Cleaner Production	S, I		X	x	x	x	
101	Sustainability assessment of universities as small-scale urban systems: A comparative analysis using Fisher Information and Data Envelopment Analysis	Ning Ai, Marc Kjerland, Cynthia Klein-Banai, Thomas L. Theis	2019	Journal of Cleaner Production	S		X	x	x		
102	Planning regional sustainability: An index-based framework to assess spatial plans. Application to the region of Cantabria (Spain)	Soledad Nogues, Esther Gonzalez-Gonzalez, Ruben Cordera	2019	Journal of Cleaner Production	S, E, I		X	x	x	x	
103	Evaluation of urban ecological well-being performance in China: A case study of 30 provincial capital cities	Jing Bian, Hong Ren, Ping Liu	2020	Journal of Cleaner Production	S		X	x	x	x	
104	Holistic methodological framework for the characterization of urban sustainability and strategic planning	Eleni Feleki, Christos Vlachokostas, Nicolas Moussiopoulos	2020	Journal of Cleaner Production	S, E, I		x	x	x	x	

Table A1. *Cont.*

#ID	Title	Author(s)	Year	Journal	Energy (E), Sustainability (S) and Infrastructure (I) Infrastructure (I)	System Dynamics	Sustainability Assessment	Economic	Environment	Social	Technology
105	jobs: Revisiting urban sustainability from access to jobs: Assessment of economic gain versus loss of social equity	Mengbing Dua, Mengxue Zhao, Yang Fu	2020	Environmental Impact Assessment Review	S		x			x	
106	Integrating the three-line environmental governance and environmental sustainability evaluation of urban industry in China	Runhe Cheng, Wei Li, Zhouyangfan Lu, Siyang Zhou, Chong Meng	2020	Journal of Cleaner Production	S, I		x	x	x	x	

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