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Published in:
International Journal of Sustainable Energy Development

DOI:
10.20533/ijsed.2046.3707.2022.0059

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

STEEP Analysis of Energy System Transition to Sustainability

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Abstract

This paper explores the complexities of the energy system and its transition to sustainability. Energy is a pervasive human need and has underpinned human development and wellbeing. World energy use has grown dramatically since the rise of civilisation and is interwoven with discoveries of sources and uses of energy, especially the exploitation of fossil fuel resource stocks and the assembly of energy system infrastructures. The current energy system is based on fossil fuel which presents some sustainability challenges. These include its finite nature, environmental pollution, and geographical imbalance between energy resources and energy use creates uncertainty and instability of supply with implications on energy security. This calls for a need to transit for fossil fuel to a sustainable energy system. The energy system is a complex system that has multiple interactions between variable within its system and outside a larger system, therefore presents feedbacks, delays and non-linearity. Most countries are striving for sustainability and thus are revaluating their energy system, which at present is far from sustainable. Sustainability requires that social, technology, economic, environmental and political (STEEP) are considered in the process of this transition. The transition of an energy system from fossil fuel to sustainability presents many challenges as the energy system interacts with all sustainability dimensions, therefore making it a complex venture. A sustainable energy system is a holistic concept that encompasses, but extends well beyond, sustainable energy resource. This paper uses Systems Thinking methodology in analysing the energy system and explaining the complexities of its transition to a sustainable state. It is a holistic approach to analysis focused on the ways a system's constituent parts interrelate and how systems work overtime and within the context of a larger system. It posits that system behaviours results from the effect of reinforcing and balancing processes. It also pays attention to feedbacks and delays which could cause disruptions in the system. This paper utilises secondary data to analyse the current fossil fuel energy system with the aim of providing a better understanding to help policy makers with decision making on sustainable energy pathways.

Keywords: Energy system, Transition, Sustainable energy, Systems Thinking

1. Introduction

Energy is a pervasive human need. Human development is underpinned by energy sources of various kinds that are essential for human wellbeing. World energy use has grown dramatically since the rise of civilisation. The evolution of modern industrialised society has been interwoven with discoveries of sources and uses of energy, especially the exploitation of fossil fuel resource stocks and the assembly of energy system infrastructures. Fossil fuels provide 80% of the world's energy consumption (Figure 1) and the energy system is responsible for 76% of global greenhouse gas emissions [1], raising the issue of its sustainability.

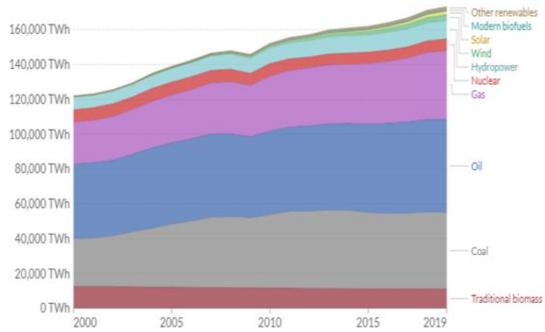

Figure 1. Global Primary Energy Consumption [2]

The principle of sustainability issue with fossil fuel is the environmental side-effect of the energy sector due to the prospect of global warming resulting from an enhanced greenhouse effect induced by combustion-generated pollutants. Environmental pollution is therefore considered a global concern. Another sustainability issues with the fossil fuel energy system stems from its finite nature. The demand for finite petroleum reserves are on the increase resulting from increasing energy demands due to expanded civilisations and populations. These have raised concerns over the limited energy resources. The earth and its fossil resources are finite, therefore the obvious implication that fossil fuels cannot be used indefinitely. The question is not when the resources will run out, rather when they will become too expensive or technically challenging to extract.

The uneven geographical distribution of energy resources presents another sustainability challenge. This geographical imbalance between energy resources and energy use creates uncertainty and instability of supply with implications on energy security. Figure 2 demonstrates the sustainability issue of fossil fuel energy system. There is therefore a call for sustainable energy system that meets the needs of the present without compromising the ability of future generations to meet their needs [3]. This means that sustainable energy system requires a balanced composition between energy security, social equity, economic development, and environmental protection. A large component of this would be the incorporation of renewable energy into the existing energy mix, but it does not eliminate the efficient use of conventional sources to ensure sustainable energy security. The ultimate objective of the energy transition is the decarbonisation of the global energy system in order to achieve net zero emissions and a global temperature rise of no more than 1.5° C by the end of the century.

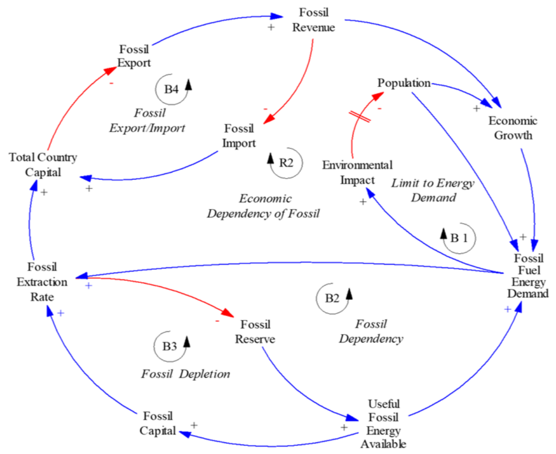

Figure 2. Sustainability Challenges of Fossil Fuel Energy System

The current energy system was built around the fossil fuel, the eventual replacement of hydrocarbons by renewable power and other forms of decarbonised energy will be fundamental to this process. Nevertheless, it is important to recognise that the transition as a process of moving from one state to another, must involve the understanding and management of the decline of the existing energy system as well as its transformation towards a future state. Policymakers have set countries on this essential road, and technology is the key to accelerating the process, but many complex questions remain to be resolved to avoid the transition becoming disorderly. The transition of an energy system from fossil fuel to sustainability presents many challenges as the energy system interacts with different sectors such as social, technology, economic, and environment, therefore making it a complex venture. Sustainability requires that the four legs social, technology, economic, environmental and political (STEEP) are considered to be equally important, thus sustainable energy resources must be economically viable, politically supported, socially equitable, and environmentally acceptable. The interaction of these sub systems present complexities, feedback and delays, thereby calling for better understanding. This paper sets out to explore the relationships between the energy system and the STEEP subsystems using Systems thinking methodology for better understanding of how to move same to a sustainable state.

2. Complex Relationship between Energy and Sustainable Development

Energy interacts with the three elements of sustainability (economic, social and environment) and therefore is intertwined with sustainable development. 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 [4]. Energy resources are found in the environment either as renewable and non-renewable sources. These are then converted to energy carriers such as fuels, electricity, and thermal energy [5]. Energy services is needed for most activities, in all sectors of the economy and provide good living standards and lifestyles, as well as social and cultural development. Energy is crucial for economic development as it is used for industrial process, transport, and for societal needs such as cooking and heating [2]. Energy therefore has critical impacts on the economic, environmental, and socioeconomic dimensions of human well-being [6]. As the world develops and population increases, additional energy is needed to drive economic activities [7]. Sustainability of the energy system is said to be central to achieving sustainability challenges such as emission reduction, increased reliability in energy supply, utilisation of renewable energy, improved energy efficiency and improved quality of life). [8] also identifies energy as an underpinning element in achieving Sustainable Development Goals (SDGs) and explains that the implementation of other non-energy related goals has bearings on sustainable energy pathways.

[9] argue that the realisation of the Sustainable Development Goals (SDGs) in SSA region depends heavily on energy. The authors further argue that when energy goal is achieved, other goals will be significantly impacted; energy (goal 7) drives industry, innovation and infrastructures (goal 9), then responsible consumption and production (goal 12) are achievable under a decent work condition which promotes economic growth (goal 8). With buoyant economy comes collective prosperity which reduces poverty (goal 1), combats hunger (goal 2), and

promotes quality living and well-being (goal 3). Sustainable cities and communities (goal 11) are products of environmental-friendly and cheap energy production as demonstrated in Figure 3. The [10] survey also identified energy system transformation as a core element of the sustainable development agenda that will improve the living standards of people with equity and environmental sustainability.

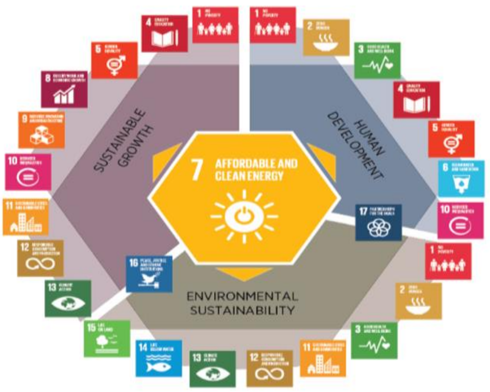

Figure 3. The Role of Energy in Sustainable Development Goals [11]

The relationship between energy (production and demand), economic growth, society and environment is demonstrated in Figure 4 using Casual Loop Diagram.

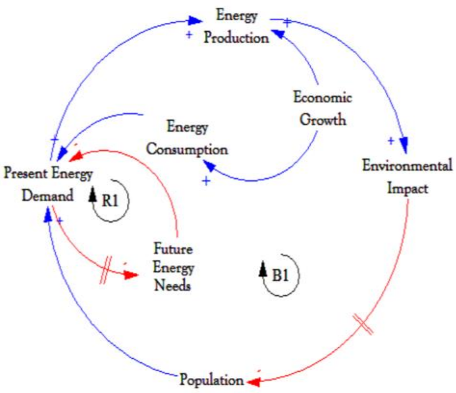

Figure 4. Causal Relationship between Energy Nexus and Sustainable Development

It demonstrates that Present Human Needs (energy) would increase as Population increases, which has a positive influence on Energy Production. Energy Production is further driven by Energy Consumption and Economic Growth. As Energy Production increases, Environmental Impact (such as climate change) also increases. As time elapses, Population decreases due to Environmental Impact if left unchecked. This feedback loop continues as a dynamic complex relationship. The argument in respect of sustainable development borders around the feedback loop between Present and Future Human (R1). There is therefore need to reduce the environmental impact of energy use (B1) without slowing down economic growth (especially in GS).

3. Inherent Dynamic Complexities of the Energy Systems Structure

According to IPCC, an energy system encompasses all components related to production, conversion, delivery and use of energy. Energy systems usually are very complex and call for knowledge deriving from all scientific fields to be developed and managed. The concept of an energy system is evolving as new regulations, technologies, and practices enter into service due to the need for transition to sustainable energy. The energy system interacts with other sectors (sub systems) such as the economy, environment and society (which in themselves are also systems), making it hierarchical. Components or subsystems interact on different levels. On a given level, components are relatively free to operate, but they are dependent on higher (slower changing) and lower (faster changing) levels 12]. Since control is distributed, each actor's span of control is limited, and steering actions will often not yield to the desired outcome. All actors, however, operate in and interact through the economy where the rules and regulations are sets and enforces by the government even though their actions and operations may be driven by demand, innovation, resource availability, technological capability etc. The energy system is characterised by many authors as a socio-technical system as it comprises of heterogeneous elements like technology, policy, markets and society [13]; [14]; [15]. All these make the energy sector an inherently dynamic and complex system with many components that have complex cause-effect relationships generated through multiple feedback loops.

Furthermore, the system cannot be predicted by understanding each of the component elements in isolation [16] therefore is said to be self-organising. The introduction of a new technology (an object) for example, will influence the behaviour of one or more people (agents), which leads to direct and indirect effects (such as resilience, security) on other parts of the system. Energy system exhibits complex social and technological dynamics. These include the complexity inherent in the technological systems and infrastructures by which energy is converted, transmitted and distributed in order to provide useful energy services to households, industry and businesses, and in the related actors and social institutions, policies and practices that influence these systems [16].

The system also consists of diverse supply sources, complex utilisation, influenced by various internal (e.g., demand fluctuations, energy policy developments and socio-economic-ecological

 | DOI: 10.20533/ijsed.2046.3707.2022.0059

systems) and external (e.g., political instability, natural disaster and energy dependency) factors [17]. The authors further argue that these complexities mean that energy managers and planners make decisions under uncertain environments, and thus the development of the sector in a sustainable manner faces many challenges. The challenges include growing energy demand, depletion of fossil fuels, threats of pollution from energy emissions and global warming. The high energy dependency, lack of energy efficiency development and uncertain policy towards the development of renewable energy (RE) are other key challenges (ibid). Energy infrastructure systems are also evolutionary as they exhibit path-dependency and lock-in. Emerging trends in the energy industry have also exacerbated the dynamic complexities of energy systems and directly affect energy policy formulation and implementation. These include widespread deregulation in electricity markets and technological advances, global environmental concerns, trends in global climate change and multiple stakeholders' involvement [18].

Sustainability in the energy sector is argued to be very complex due to these dynamic complexities. Four main complexities identified in literature include; system uncertainties, nonlinear relationships between system variables; time delays; feedback structures and causal relationships between system variables [19]; [20]. This paper posits that it is important to understand systems variables and their interactions to effectively analyse the behaviour of complex systems, such as energy system.

System uncertainties occur in form of unprecedented change in the energy system [18]. There has been an exponential increase in energy demand, usage and investment (especially in GS) leading to unprecedented dynamic imbalances in the energy system. This is further complicated by influences of unpredictable change in government subsidy and incentives, technological innovation, price fluctuations resulting from demand-supply dycotomies as well as imprecise human perception [21]). These and other system variables pose serious difficulties in energy policy formulation. Dynamic complexities can also occur due to the energy system's non-linear reaction to an action [20].

Using electricity as an example, a price decrease would lead to increased industrial use, however, as a result of maximum production capacity as a limiting factor for desired consumption, the electricity usage will reach saturation point eventually even if the price continues to fall [22]. Such non-linear relationships between energy system variables are difficult to analyse using mathematical and econometric programming models and make planning in this sector a complex process [19]. Consequently, appropriate modelling techniques for addressing such complex dynamic non-linear relationships are required for effective policies and planning as posits by this research.

The energy system is also faced with inherent time delays present in energy projects and innovation. Energy projects undergo several stages such as project and funding approval, design, construction and installation causing time lags in form of material or information delays. These delays impact shareholders, investors, energy policy makers and cause dynamic uncertainties in policy development [18]. Therefore, energy policy formulation approaches that address the inherent dynamics of time delays are most desirable. The underlying feedback structures and dynamic behaviors of energy systems (Figure 5) include trends in energy prices, consumption, carbon emissions and renewable energy technologies adoption [23]. The increase in population and economic growth increase energy demand and widen the demand-supply gap, leading to the need to add more capacity which in turn requires investment. The investment in additional capacity will often experience delays. However, adequate energy supply may influence economic growth and population growth, which may further lead to increased demand. This cycle continues until the demand is fully met, with capital investment efforts eventually reduced or stopped. Here the demand-supply gap acts as a feedback mechanism illustrated by the demand, investment and supply variables in the above discussion. To provide appropriate energy policies, the identification of feedback mechanism using appropriate tools and approaches are crucial for the energy systems.

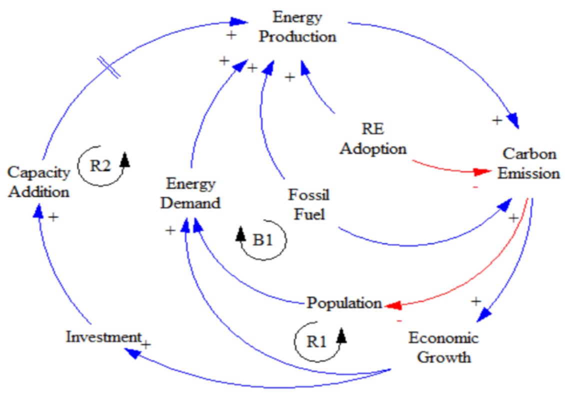

Figure 5. The Feedback Structures of the Energy System

Causal relationships between system variables are also a major concern to energy planners in the medium- to long term [19]. The investigation of how regulatory policies, incentives and subsidies on energy supply mix and prices influence the economy, energy resources and the environment are important. The complex dynamics of the causal linkages between system variables need to be addressed and analysed adequately to formulate cost-effective and sustainable energy policies [24]. This paper argues that given these complexities, it is essential to develop systems analysis approaches that can be used for development and evaluation of energy system policies, both at tactical and strategic levels.

4. Energy System Transition

The concepts of transition as it relates to the energy system is used to study its sustainability to solve the problem of climate change. Sustainable energy transition is generally understood as a concept of developing robust, effective and efficient energy sectors in a particular country or region without compromising the present and future socio-environmental security [25]. Historically, the first energy transition that occurred was fuel switch from wood to coal following the first industrial revolution. The second global energy transition occurred when oil became dominant energy source in beginning of 20th century, replacing coal (though coal still remains a component) [26]. Literature suggest that past energy transition was characterised by a depletion of energy source, an increase in the price of dominant energy as a result of scarcity; negative environmental/health impact; introduction of new energy source at a competitive price and efficiency; geopolitical and economic factors influencing national security. It is also noted that transition in the energy system usually spans decades and entail combination of external influence, actor behaviour and actor interaction which is dynamic and complex. Therefore, it displays emerging property of a large-scale socio-technical system. In the context of public policy, this calls for the need to understand how to evoke a transition, while acknowledging the complexity of these vast systems and the roles all the players as the energy system continues to evolve.

Energy system transition has also been portrayed in literature as a wicked and complex adaptive system with interrelated, heterogeneous elements (agents and objects) [16]. The energy sector is evolving rapidly and the current transition is shaped by combination of many factors, including the realisation that energy is a key enabler for achieving development goals but also a key player in climate change. [27] and [28] argue that energy transition poses the challenge of managing multiple goals and objectives, but also presents the opportunity of moving society towards an energy future that promotes sustainability. Furthermore, because energy transitions are embedded in wider political, social and economic contexts, they have the potential to worsen these wicked problems by either exacerbating existing inequalities or introducing new vulnerabilities [29]. This calls for a shift in thinking and approach to energy policy and strategy design that imbibes the core message of sustainability 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 [30].

Transition challenges are made complex by the existing energy policy institutions which are not designed for this task; accelerating pace of technological change and the needed energy policies to support them; and decision making on the variety of available energy resources and technologies. Energy transition policymaking is a complex and multi-dimensional that require long-term economic planning involving huge investments, multiple stakeholders, long-term planning and investment as well as overcoming the structural internal and external dependency of energy systems [31]. 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 [32]. Furthermore, it involves a larger volume of variables, which are interlinked and crossover the economic, societal, environmental, and technological dimensions of society [33]. It also 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 [34].

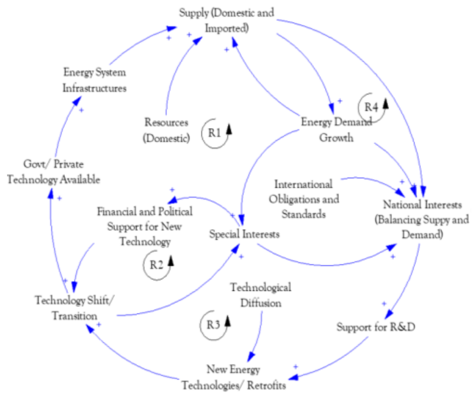

Figure 6. Complexity of Energy System Transition Policymaking

The Figure 6 demonstrates relationships within an energy system in relation to their transformation, considering the complexity of energy transition policymaking. 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 not only beneficial but mandatory.

5. Methodology

We used the System Thinking methodology in analysing the energy system and explaining the complexities of its transition to a sustainable state. Systems thinking was developed by Professor Jay Forrester, in 1956. It is a holistic approach to analysis focused on the ways a system's constituent parts interrelate and how systems work overtime and within the context of a larger system. This approach contrasts with the traditional analysis which focusses on breaking them down in separate elements. System thinking has been used in different research areas such as medical, political, environmental and energy. System thinking posits that behaviours results from the effect of reinforcing and balancing processes. A reinforcing loop leads to the increase of some system component which if left unchecked by a balancing process, will cause the collapse of the system eventually. A balancing loop is one that tends to maintain equilibrium in a particular system. It also pays attention to feedbacks and delays which could cause disruptions in the system. This is extremely important as sometimes, the variable causing a system disruption from be far removed from the particular system but a part of the larger system. An example in this research is the social-technical relationship in an energy system. Where even though the renewable natural resources and the technology are available, yet the social and political domain could actually prevent or slow the uptake of this.

6. Discussions and Analysis of STEEP Subsystems of Sustainable Energy Transition

The Social Domain - Population is a key important factor to determine electricity demand. Higher population level is expected to increase electricity consumption. A positive correlation between population growth and electricity demand is therefore expected. With higher energy demand, the cost of energy will likely increase, leading to a lower supply of energy. This then lowers electricity production as the supply of energy is low. Consequently, the population with access to electricity in percentage would decrease. It is noted that in ORSSA, urban household energy use accounts for a large proportion of commercial fuel consumption. As population and principally urbanisation increase, consumption is expected to rise rapidly in the future [35]. The information on the utilisation pattern and factors driving consumption of population is important for the national energy planning framework and for deriving strategies for a more rational energy utilisation and increased reliability of energy supply. Future population growth is therefore a key factor in energy planning especially in ORSSA, where there is already unmet electricity demand as well as future energy needs to take into consideration.

Loop B2 in the Population CLD (see Figure 7) demonstrates that as population increases, the number of resources per person falls, and when this happens, the average Life Expectancy will also fall since fewer resources means less energy, a weaker economy, fewer health infrastructures etc. As Life Expectancy falls, the rate of Deaths increases, causing a decrease in the Population. This balancing loop will only come into play where resource constraints are a serious issue as seen in ORSSA economies. The effect of climate change also interplays with Life Expectancy. It has a negative impact due to the effect of pollution on human health. A rise in life expectance (people living longer), death rate falls and the results in increase in population. When Life Expectancy falls and infant mortality rates increases, people may desire to have larger families leading ultimately to more children per household with resultant increase in the Population. This exacerbates resource constraints and decreases Life Expectancy further. This reinforcing loop(R3) represents a vicious cycle where people essentially get what they want in the present at the expense of the future.

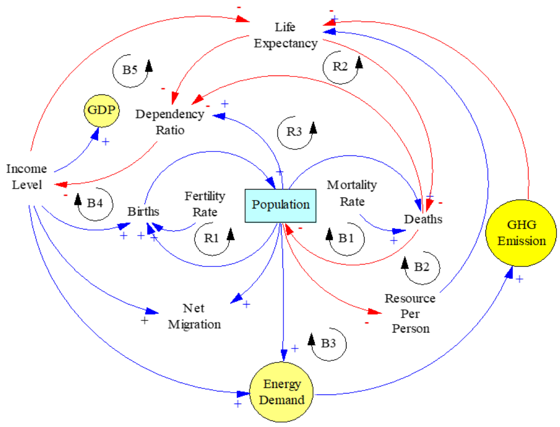

Figure 7. Causal Loop Diagram of the Social Domain

A steady population increase would lead to steady increase in energy demand therefore calling for a planned capacity addition. Where this is not carefully planned, it can lead to energy security issues. The Social Module is therefore a critical sector for long-term evaluation of the energy system transition due to its influence on the behaviour of other important model variables such as energy demand, energy use per capita, GDP per capita, electricity consumption per capita and several other indicators. This Module is also important in estimating access level, which remains one of the key objectives of transition in developing countries.

The Socio-Technical Domain - This module consists of two (2) major loops: The Technology loop and the Socio-technical loop (see Figure 8). The technical loop (B1) describes the capacity addition and life cycle process of different energy production technologies, capacity factor and lifetime of the different technologies, capacity under construction, construction time (with resultant delays in capacity addition), and the decommissioning. These technology variables interact with the society through energy demand and supply and their dynamics (R1 loop). For example, as population (Social module) increases, energy demand increases which in turn requires increase in energy production. Energy production also interacts with the GDP (Economic module) through energy demand. An increase in economic activities due to GDP growth would lead to increase in energy demand which again would require increase in energy production.

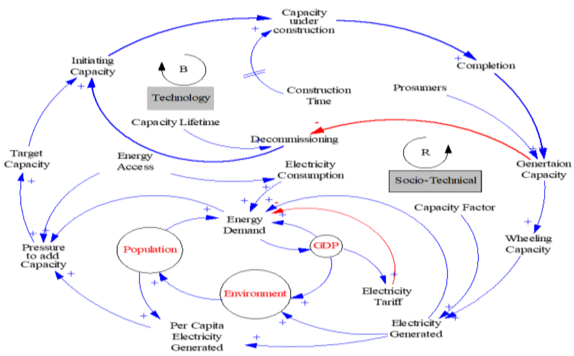

Figure 8. Casual Loop Diagram of the Socio-Technical Domain

The increase in energy demand resulting from both population and GDP growths will in turn lead to increase in GHG (Environment module) depending on whether renewable or non-renewable technology is used in energy production. These interactions lead to multiple dynamics and complexities that need better understanding. It can be seen that although the Social (population) and Economic (GDP) module are different systems in their own right, and sub-system in STEEP, they exert significant influence of the energy production system. Where not well understood, policies targeted at energy production could have unintended consequences on these other sub-systems.

Economic Domain - Fossil energy is the material basis of human survival, economic development and social progress. In any economy, energy consumption and economic growth are closely related. Since the industrial revolution, both the world economy and energy consumption have grown rapidly. The rapid development of economy has further increased human society's dependence on energy, leading to increase in energy consumption. However, the production and use of energy have negative impact on the environment, and the deterioration of environment will restrict regional economic development, thereby affecting the exploration and utilisation of energy. This relationship creates complexities and feedback loops as described in Figure 9.

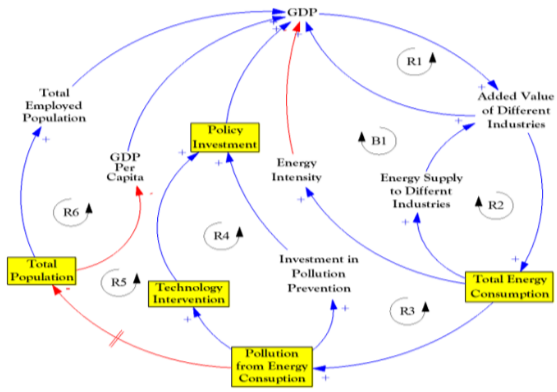

Figure 9. Casual Loop Diagram of the Economic Domain

The Economic Module helps in analysing the energy–economy–environment (3E) system. In the 3E system energy sustainability is the basis, environmental sustainability is a condition, and economic sustainability is the ultimate goal. The coordinated development of energy, environment, and economy is critical for economic and sustainable development. Figure 9 has 6 positive loop and 1 negative loop. In Global North, different industries as well as taxes from employment contribute to the GDP as seen in Loops B1 and R5. These industries require energy for production of good and services and therefore have impact on energy consumption and supply (Loops R2 and B1). The more this energy use is based on fossil fuel, the more the environmental impact will be (Loop R3). There is the need to reduce the energy intensity from GDP to reduce energy consumption for GDP growth (Loop B1). The pollution from energy use has negative impact on the environment, which will call for technological and policy intervention (Loop R3 and R4) especially because if left unattended to, pollution has negative impact on population over time (R5). The population also has impact on the GDP through Income per capita and the number of people employed in the society (Loops R5 and R6). Figure 9 demonstrates the interconnectedness of the economic module to the socio-technical, population and environment as highlighted in yellow.

Environmental Domain - The environment subsystem is represented by three variables: the source of electricity generated, emission factor of each type of technology/ fuel used in electricity generation, and the relative level of environmental pollution. These are closely related with the other subsystems (see Figure 10). The core of the environment subsystem is the type of fuel as well as the technology used to generate electricity and how much pollution that result from its use. For example, coal is seen as ’dirtier’ than gas and has a higher emission factor. A key measure of the environmental cost of any economy is the electricity generated emission intensity which simply put is how much pollution is produced per US Dollar to fund the economy (GDP). Electricity generated emission intensity is used to measure the overall emission produced per unit of output, typically expressed in mega joules per US dollar (MJ/US$) of GDP or value added. It is widely used to represent the overall energy productivity of an economy or sector. Factors that can contribute to electricity generated emission intensity include end-use appliances technologies, generation fuel/technologies, changing patterns of energy end use; changes in the structure of the economy (e.g. shifts toward higher shares of the less energy-intensive services sector) and lifestyles changes.

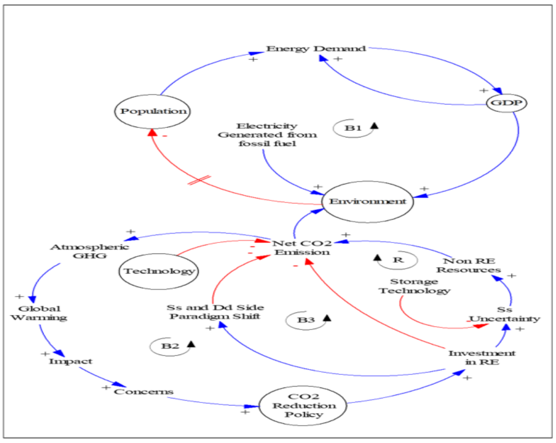

Figure 10. CLD of the Environmental System

It can be noted in Figure 10 that there are 4 loops (3 balancing and 1 reinforcing). Loop B1 demonstrates the relationship between energy demand as a result of population increase and industrialisation can increase environmental degradation if fossil fuel is source of the energy. If environmental degradation is not curtailed, it could lead to health issues and reduce population over time. To reduce the net CO2 emission (Loop R1)that polluted the environment, technology and policy can be used for intervention as seen in Loops B2 and B3.

7. Conclusion

Continued use of fossil fuels that now supply 85 percent of our energy needs leads to challenges of environmental degradation, diminishing energy resources, insecure energy supply, and accelerated global warming. Changing to alternate sources of energy requires decades, to develop new technologies and, once developed, to replace the existing energy infrastructure. Unlike the historical change to fossil fuel that provided increased supply, convenience and functionality, the transition to alternative energy sources is likely to be more expensive and less convenient. Arriving at a successful outcome will involve an assessment and understanding of all interconnections, feedback loops and time delays associated with the energy system. A full understanding of how the current energy value chain may be restructured over the next two to three decades is equally important. This will involve analysis of new technologies, government policies, regulatory frameworks, consumer preferences, the interaction between different energy vectors, an understanding of varying regional and sectoral perspectives, risks and uncertainties, a willingness to develop new business models, and an appreciation of the potential geo-political consequences of the energy transition.

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 | DOI: 10.20533/ijsed.2046.3707.2022.0059