A systems dynamics approach to understanding the biofuels socio-technical transition.

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Abstract

Biofuels are renewable energy sources that are alternatives to petroleum fossil-fuels. Since energy is a domestic necessity and also a factor of production (enabling a variety of services such as transportation, heating, and food production), the widespread production and use of biofuels can facilitate low-carbon, resource-efficient and socially inclusive economic development. However, biofuels do not automatically deliver these development benefits. If managed incorrectly, biomass can be harvested at unsustainable rates, cause increases in emissions and environmental pollution, displace food security and livelihoods, and increase poverty. Therefore, appropriate management and governance will be needed to ensure that the biofuels transition is tailored to the local social, economic, and ecological context.

Responding to this challenge dictates that new concepts and research tools be applied to represent and model complex systems. In addition, a multi-level perspective is needed to reveal the scale and levels of hierarchy in the system and understand the biofuels market uptake and diffusion.

This chapter uses System Dynamics tools and a multi-level approach in order to reveal the various factors that will influence the transition to a biofuels socio-technical system, and to identify components that will regulate the behaviour of the biofuels system. Different stages of the biofuels system (biofuel feedstock production, biofuels production, and biofuels market uptake) were analysed using Causal loop diagrams in order to identify influencing variables and reveal important regulating feedback loops that determine the systems behaviour. This revealed that the transition to a sustainable biofuels future would require a spectrum of wide interrelated changes. The multi-dimensional shift from the current fossil based regime to a biofuels regime will require changes in technology, markets, user practices, social and cultural preference, policy and governance. Considering the established petroleum dependency of the existing energy system, the transition to a biofuels future will need a coordinated and systems approach so that biofuels contribute to a new green economy and a sustainable development pathway.

Key words: system dynamics, simulation and modelling, biofuels, socio-technical system, renewable energy

1. Introduction

Biofuels are a renewable energy fuels derived from biomass. Biofuels include liquid, solid and gas fuels (i.e. wood-pellets, biogas, bioethanol and biodiesel) that are used to deliver energy services such as heating and cooling, electricity and transportation. Biofuels can deliver a range of benefits to society; such as reduced greenhouse gas emissions, a reduction in the dependency of finite fossil fuels, and new opportunities for agriculture and socio-economic development.

However, there is some debate whether biofuels contribute to or ameliorate problems such as food supply and security, soil nutrient depletion, soil erosion, water demands, greenhouse gas emissions, biodiversity loss, air pollution, and productivity loss (Adler *et al*, 2007; Jordan *et al* 2007 and Stone *et al* 2010). In addition, the land use changes that may be needed for biofuels feedstock production can result in considerable impacts. Agriculture expansion and the fuel-intensive farming practices used, are responsible for a significant portion of the global green-house gas emissions (Duxbury 1994; IPCC 1997). Furthermore, the use of land-resources for biofuels can result in a competition with food production and other valuable biomass products (fodder, timber, fine chemical, fibre and textile production). Many of these differences in costs and benefits can be attributed to context-specific issues such as past land-use, crop preferences, management practices, and the prevailing environmental and social conditions where the feedstock is grown (Robertson *et al* 2008; Scharleman and Laurance 2008; Kline *et al* 2009). Therefore, the complex interactions between agricultural activities, local ecosystems and society require that agricultural planning and practices need to be well understood, integrated and effectively managed. If developed appropriately, sustainable bioenergy projects offer not only an opportunity for the production of renewable energy and the displacement of fossil fuels as energy sources, but also the development of more integrated and sustainable agricultural systems that are based on energy efficiency and improved natural resource management (de Vries 2010, IAASTD 2008).

There are various biomass sources that can be converted by thermochemical, physical-chemical and biochemical processes to biofuel products. These biofuels can be used for heat, electricity or shaft-power (transportation). Biofuels are produced form various biomass feedstocks; such as wood-fuels, agro-fuels and various industrial and municipal wastes. Wood fuels include all types of woody biofuels derived directly and indirectly from trees and shrubs grown on forest and non-forest lands. Agro-fuels are biofuels obtained as products of agriculture and co-products from farming, and or industrial processing of agricultural products; and include agricultural crops, agricultural residues, and dedicated biofuel crops. Municipal and industrial wastes are produced by urban populations, including residential, commercial, industrial and public. These are solid wastes typically sent to land-fill and the liquid wastes that are often treated at wastewater treatment plants and consist of biodegradable and non-biodegradable components.

A range of conversion technologies can process these biomass feedstocks into biofuels (Jumbe *et al,* 2009). Various biofuels can be produced (bioethanol, biodiesel, biogas, biomethanol, biobutanol, biohydrogen, and biosynfuels), but only bioethanol, biodiesel, and biogas are currently at established commercial stage and have been termed conventional biofuels (IEA, 2010). These biofuels are technology mature and therefore can be readily adopted with relatively little technology risk. In addition, they offer easy opportunities to displace petroleum fuels, since they can be used in combustion engines either alone or by blending with petroleum fuels. Bioethanol and biodiesel are the most established biofuels, because these are produced through established methods and can be distributed in existing transport and infrastructure with little or no modifications.

The biofuels feedstock is converted into biofuels via three pathways:- bio-chemical, thermo-chemical and physico-chemical. There are several stages of the product life cycle: biofuels feedstock production, transportation, biofuels production, distribution to market and end use- Figure 1.

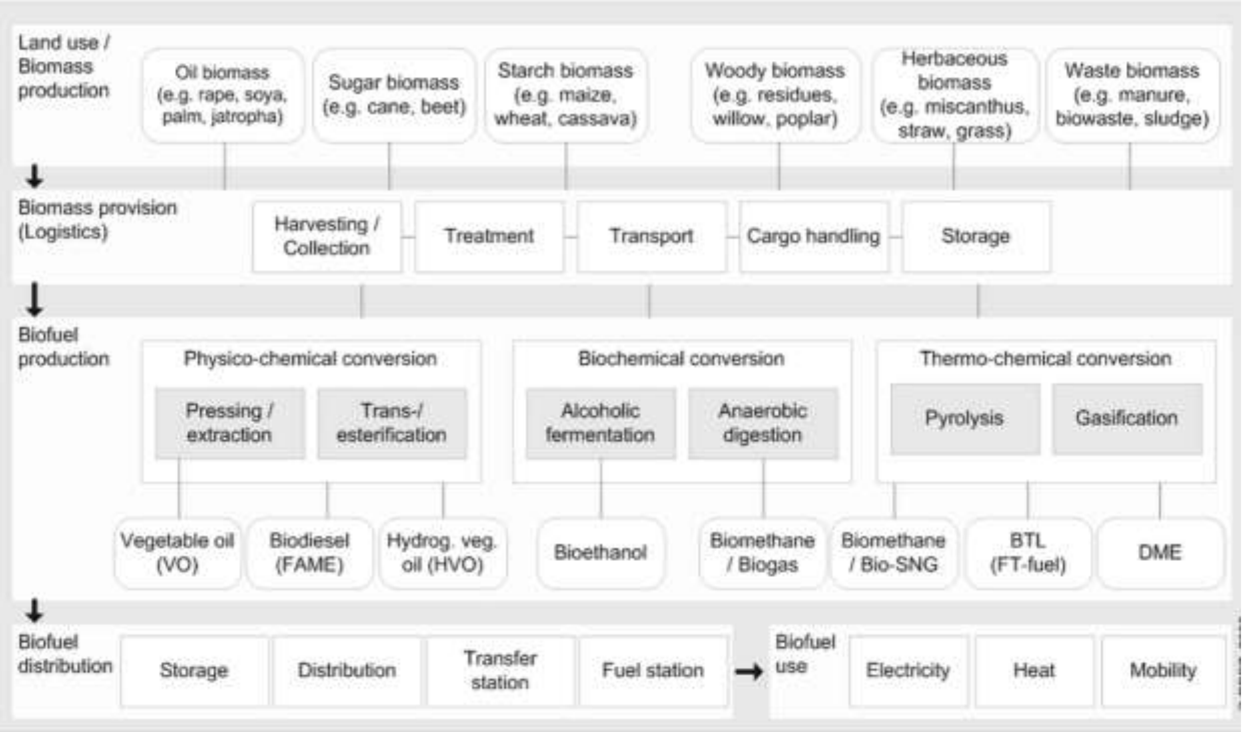

Figure 1 An overview of different biofuel systems, including the different steps involved along the pathway (Perimenis *et al*. 2011).

The transition from an energy system based on fossil fuels to one based on renewable fuels is not only a technical matter, since it depends on the social behaviour, values and strategies of individual actors and institutions; as well as policies, regulations and markets that will shape the energy system. Understanding how such socio-technical energy transitions might be brought about is a major trandisciplinary research challenge. A multi-level perspective views biofuels development as Socio-technical system that consists of the scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of technology. Hence, the biofuels system encompasses the production, diffusion and use of a technology; and it should respond to social needs in order to improve the well-being of society (Geels 2002 and 2004).

2. Methods: Systems thinking approach to understanding the biofuels transition

The widespread use of renewable biofuels as a replacement to petroleum fossil fuels is predicated on facilitating the required changes in broader social, economic and political systems. Technology is embedded in a complex set of other technologies, physical surroundings, people, procedures, etc. that together make up the socio-technical system. A Socio-technical transition refers to the reconfigurations between technology development and various processes in science, industry, markets, policy, and culture that will be required to move to a desired future state or trajectory. Socio-technical systems require a multi-level perspective that considers a range of social, environmental and economic criteria and how they interconnect to help determine the behaviour of the system. This systems perspective allows understanding of technology development and technology use in terms of the complex adaptive processes that constitute the interdependencies between materials and society (Russell and Williams 2002).

Biofuels encompass a highly heterogeneous set of socio-technical systems and the transition requires much more than substituting technology for the conventional fossil fuels. Biofuels require different structures in production, distribution and consumption compared to the current established fossil-fuel based economy. Biofuels fulfil socially valued functions and also condition the ways these functions are conceived and perceived; by defining possible or desirable ends and the choice of means to attain these ends. For example, the production of biogas from human and animal manures provides methane-rich biogas that can be used as a cooking fuel. This changes the perceptions of the way to achieve the provision of a cooking fuel by considering a biofuel (biogas) instead of traditional fuels (wood or charcoal). It also changes the ways that wastes are perceived, because human and animal manures are used as a valuable biofuel resource instead of presenting an environmental and a health-burden. However, if energy demands are considerably greater than supply, food may be used to deliver energy and this would lead to increased poverty, inequality and unsustainable developments. An integrated view may lead to the widespread adoption of new technologies and solutions to integrating waste treatment and management with the production of and energy and other valuable products.

Therefore, the transition to biofuels on a wide scale requires careful and considered strategies and plans to ensure that they further low-carbon, economic growth and sustainable developments. The transition from one energy regime will face challenges of maintaining a coordinated and sustainable pace across sectors, due to the inherent complexity and the difficulties in managing such a transition. A lack of careful planning and co-ordination may lead to negative impacts; such as the use of arable land needed for food production; the use and control of limited resources such as land, water, soil nutrients and genetic resources; loss of biodiversity; unintended greenhouse emissions from direct and indirect land use change; and deepening problems with land tenure, and governance (Upham *et al* 2009; Tomei and Upham 2009).

A systems thinking approach has been applied as the method of choice to understand the biofuel socio-technical transition. This is based on a wealth of knowledge and modelling of system dynamics and complex social systems (Richardson 1991; Sterman 2000). This approach to the biofuels transition helps to reveal the complex, multi-scale, adaptive and emergent properties of a biofuels transition and thereby can support sustainable development (Smith and Stirling, 2007). Systems thinking and Causal Loop Diagrams (CLD) are used and tools to capture the interrelationships between heterogeneous actor groups and networks, institutions, guiding rules, technology, resources, and infrastructures are important elements of a socio-technical system. These diagrams can represent relationships between elements which are difficult to describe verbally, and can describe circular chains of cause-and-effect. This feedback results in self-regulation and will determine the behaviour of the whole system (Goodman, 1989 and Sterman 2000, and Richardson, 1986). The CLD helps to create a understanding how changes manifest in the system, and can explain behaviours such as path dependence, lock-in, or path creation. CLDs also provide the basis for developing endogenous explanations of socio-technical transitions, by helping to weave together process theorizing from distinct perspectives, and making the information available to decision-makers in a useful way. CLD use display casual interactions or relationships and their polarity, and feedback loops may help to regulate behaviours. A positive feedback loop reinforces change, often at an ever-increasing rate. In some situations a rate of change may, during the early stages of influence on a particular system relationship, appear to be minor (i.e. the cause of change and the change itself may seem insignificant); however, as the change becomes magnified through reinforcing effects, the system impacts thereof can rapidly assume significant proportions. A negative, or balancing, feedback loops impose regulating or stabilizing system effects, which can be either desirable or undesirable (e.g. an undesirable effect could be the resistance a feedback imposes in terms of enabling desirable system change). In addition, there can be changes that only occur after a time delay and the dynamics of change will be important in terms of how they manifest system behaviour.

3. Results and discussion: Analysis of the biofuels transition

3.1 Identifying the biofuels socio-technical regime, landscape and niche

Technology refers not only to the designed and engineered material objects, but also to the embedded components of socio-technical systems in which producers, infrastructures, users, consumers, regulators and other intermediaries are all embroiled (Bijker *et al*. 1987; Elzen and Wieczorek *et al.* 2005). In such a system, technical and social elements are co-constitutive, interacting and shaping each other with exchanges in both directions (Bijker and Law 1992). It therefore follows that biofuels are not just a series of engineered artefacts performing energy conversions. They also entail configurations of the social and technical enablers; which have emerged contingently in particular contexts, and which mirror the wider social, economic and technical relations and processes. For example, human actors are embedded in social groups which share certain characteristics such as certain roles, responsibilities, norms, perceptions that in turn affect the system.

Transitions of socio-technical regimes are considered to be complex, long term processes instigated in niches (Geels 2004). Whether intended or not, the multitude of actors involved in them makes the evolution of the niche uncertain and the transition process complex. The transition towards a biofuels led energy regime can be represented by a multi-level framework on three different levels- the niche, regime and landscape (see Figure 2).

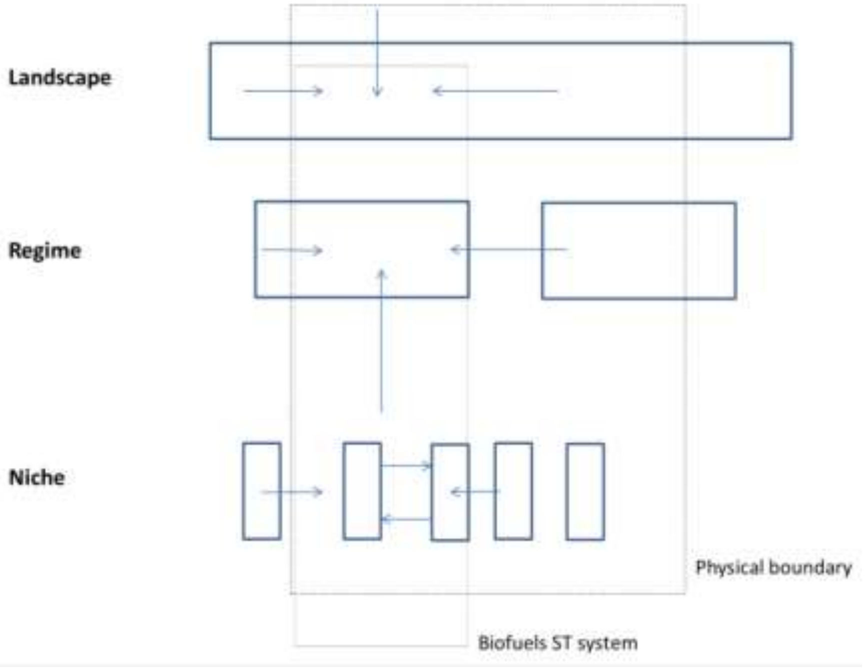

Figure 2: The multi-level level perspective of socio-technological system (Salé and Dewes, 2009). The biofuel regime will have a defined socio-technical system boundary that does not necessarily coincide with a physical boundary. Arrows indicate desired transition to the biofuels socio-technical system. Abbreviation: ST- Socio-technical.

The biofuels Socio-technical regime, landscape, and niche are identified and described below:

Landscape: The biofuels landscape lies at macro- level. Developments in the landscape level are external (not under control of separate regimes and niches) to developments in the regime and niches, but nonetheless have a significant influence on them. Examples include; material infrastructure, institutional factors, social values, beliefs, politics and culture (Geels and Kemp 2000). For biofuels developments, the landscape can be broadly defined as being composed of the: volatility in global oil/fuel prices and the 'peak oil' crisis, an increasing awareness of the impacts of air pollution and climate change from the use of fossil fuels; acknowledging the key role that agriculture plays sustainable development, and a renewed interest in low-carbon economic growth and a Green economy (UNEP 2011).

*Regime***:** The biofuels regime is composed of the dominant social, technical and economic forces that support the technology and its physical and non-physical infrastructure (Lane 2002). The dominant regime typically exerts a certain resistance against new or novel niche development; such as protectionist policies and subsidies for fossil fuels. Support for biofuels (or reduced support for fossil fuels) may be needed to help ensure that biofuel developments overcome these barriers and fulfil sustainable development imperatives. An example is the sustainability certification schemes (such as Forest Stewardship Council, the Roundtable on Sustainable Biofuels, the Global Sustainable Bioenergy project, the Sustainable Biodiesel Alliance, and the Roundtable on Sustainable Palm oil) and the standardisation of biofuels. The latter is needed so that the performance and warranty on engines are not compromised. These requirements are likely to place additional cost to vehicle owners and would be met with considerable resistance.

Niche: Niches provide space for learning and innovation. The biofuels niche provides platforms for learning processes, such as technical specifications, user preferences, public policies and symbolic meanings. Niches are locations where it is possible to deviate from the rules in the existing regime and experiment and explore new rules. A niche market develops into a new socio-technical regime by means of diffusion. This diffusion involves the communication of the technology innovation and its perceived advantages, to result in changes in the structure and function of a social system (Rogers 2003, Geels 2002). Niche markets can only truly develop and flourish if somehow supported through government mechanisms and the regime. In many developing countries such as South Africa, the lack of investment capital, the required fiscal mechanisms and supporting policies, have all hampered biofuels development. South Africa could take the lessons learnt from the newly industrialised countries such as Argentina and Brazil in the successful transition to biofuels. It could also heed some unintended consequences of biofuels development. For example, there are also various concerns that the industrial agriculture model adopted by Brazil as marginalised resource-poor farmers that depended on a multitude of agricultural and forest products for their livelihoods (food, fuel, medicine, building materials) (IEA task 40, and Smeets *et al*., 2006).

3.2 Causal loop diagrams to represent the biofuels transition

Systems comprise interdependent groups of elements forming a unified and predictable pattern. System thinking requires a departure from examining isolated events and their causes to the examination of whole systems comprising of inter-connected and interacting parts. Causal loop diagrams (CLD) are a Systems Dynamics tool used to identify and explore the relationships and effects between components of a system. The interactions between elements of the system reveal system behaviour, and can create emergent system properties which cannot be described in terms of the separate components. A CLD creates an conceptual understanding of how changes in important variables will influences the system, and can be the first step to develop a quantitative stock and flow model. The inter-related, causal variables can either change in the same direction (indicated with a "plus") or change in opposite direction (indicated with a "minus"). Processes that feedback in the same direction are called reinforcing processes (indicated with R) since they amplify the effect. Similarly, the processes that feedback to give a change in opposite direction (indicated with B) are balancing (B) or dampen out the effect. Through this approach a high level causal loop diagram that captures major aspects of biofuel production was developed (Figure 3).

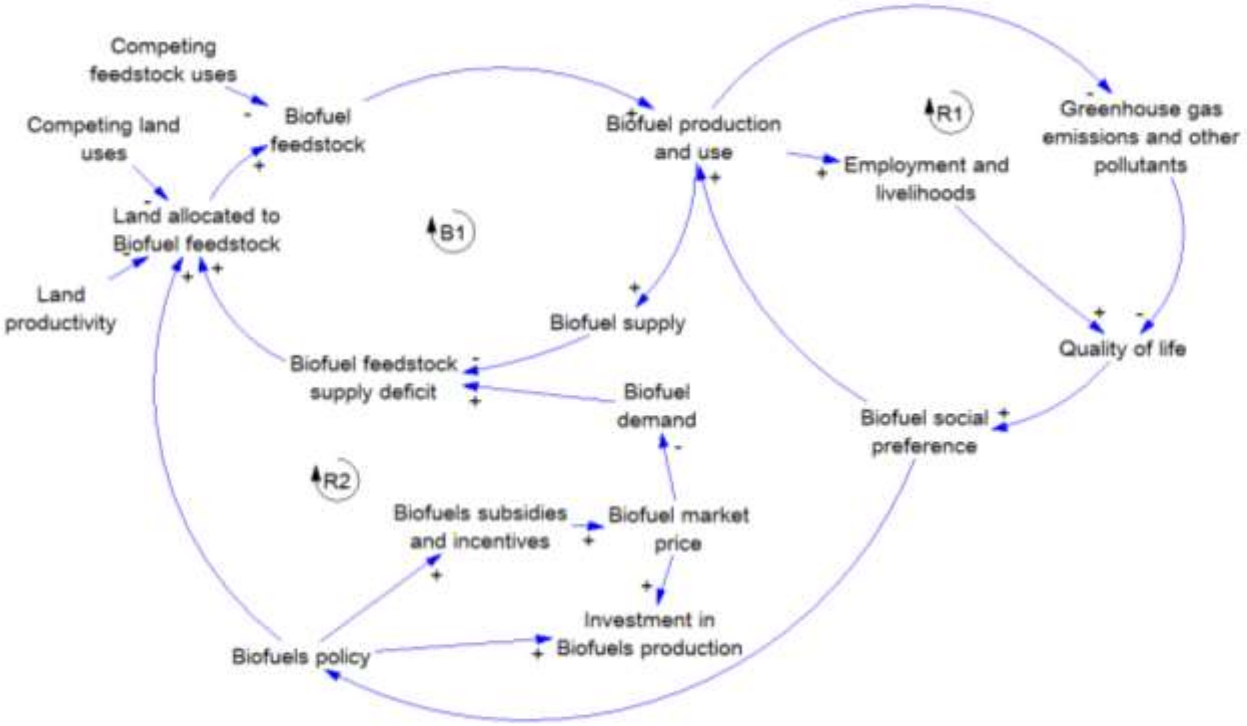

Figure 3. General Causal Loop Diagram (CLD) of the biofuels system illustrating factors that influence biofuels production and use

The recent global climate-change, food and economic crises have urged a re-orientation of the economy to a low-carbon, resource efficient and socially inclusive development path. This global landscape and the green economy (UNEP 2010) is influencing the development agenda and the biofuels transition by policy and support that increases awareness, uptake and diffusion of renewable energy and biofuels (Smith *et al.* 2005; Elzen and Wieczorek, 2005). The transition to a biofuels socio-technical system requires an appropriate regime with strong support for renewable energy and biofuels through governance, fiscal incentives and appropriate policy. In addition, since biofuels are currently in their infancy in Africa, the niche biofuels market will need to be developed with an increased uptake of biofuels by society, until biofuels become the prevailing socio-technical regime that completely displaces the carbon-intensive petroleum fuels. Such niche markets can only truly develop and flourish if somehow supported through government mechanisms and the regime. Therefore, achieving biofuels technology uptake and diffusion will require strong support in terms of governance, fiscal incentives and appropriate policy so that it can complete with petroleum fuels in terms of economic viability. The adoption of biofuels at scale in Africa can be enabled by taking a ‘latecomer advantage’ with the use of ‘tried and tested’ commercially available biofuels technology and the existing petroleum fuels infrastructure (i.e. motor vehicle engines, pipelines, refilling station).In addition, there will need to be awareness and communication of the biofuel technology innovation and its perceived advantages, so that society values biofuels beyond the competitive price set by current petroleum fuels; and thereby positivity influences their value function (Rogers 2003, and Geels 2002).

The global and national policies and incentives that support renewable energy and biofuels will drive the development of biofuels; thereby increasing the land allocated to the production of biofuel feedstock. An increase in land allocated to biofuel feedstock will result in an increase in biofuel feedstock production and use (although this will be tempered by competing uses for land and biomass feedstock). An increase in biofuels production and use will result in a reduction in greenhouse gas emissions and the emission of other pollutants, which will result in improvements in the quality of human life and the social preference for biofuels and other technologies that can reduce greenhouse gas emissions. The social preference for biofuels will in turn stimulate the development of supporting biofuels policy. This is represents the large reinforcing loop, R1.

An added component that controls and limiting an ever increasing biofuel supply, is the biofuel demand. A reduced demand will reduce the biofuel feedstock supply deficit and therefore reduce the land allocated to biofuels production, and hence reduced biofuels supply; as depicted by the balancing loop, B1. Importantly, the biofuel demand will largely be a reflection of the biofuel market price, which is in turn affected by biofuel subsidies and incentives; as well as biofuel social preference. The last reinforcing loop, R1, shows that an increased social preference for biofuels will stimulate the production and use of biofuels, which in turn will lead to reduced greenhouse gas emissions, improvements in the quality of human life (attributed to the production and use of biofuels), and thereby an increase in biofuels production and use.

Arguably, the supply of biofuels can be constrained by arable land available for food and the need to set aside land for biodiversity and conservation. A global debate exists on land available for biofuels and the competition of food and biofuel production from land and other agricultural inputs (water, soil carbon and nutrients). Many developing countries do not have legal land use systems or tenure and need to improve food production and security. An increased demand for biofuels can increased food prices. For example, there was an estimated 30% increase in grain price from 2000 to 2007 and an estimated a 20% increase of the price of vegetable oil in 2014, as a result of the effects of biofuel blending mandates on the food supply system (Rosegrant, 2008 OECD (2006). In addition, the development of biofuels may displace persons from their land on which their livelihood depends, since many land users in developing countries are not land owners with legal tenure and have only customary rights (German *et al*. 2011*,* Schoneveld *et al*. 2011). For example, despite the large number of direct and indirect jobs generated in the sugarcane and ethanol sector in Brazil, additional in-depth research into other socio-economic aspects is needed, especially on matters regarding income distribution and inequality effects, and the role the industry plays in negotiating social conflicts over land tenure (Walter 2008).

The biofuels socio-technical system can be explored in greater depth by analysing the stages of the biofuels life cycle; namely: biofuel feedstock production, biofuels production, and biofuels market uptake. The CLD developed for biofuel feedstock production, Figure 4, reveals that the biofuel feedstock market price will be a significant determinant in allocating land available for the cultivation of biofuel feedstocks. Other important external variables are land area available for biofuels production, the price of land, and land currently under cultivation for other uses. Given positive market prices and signals, the land under cultivation for biofuels will increase to increase the feedstock yields, increase the biofuels feedstock supply, and thereby reduce the biomass feedstock price. This self-regulating, balancing loop of biofuels feedstock supply, B1, will also be influenced by the potential for market saturation. In addition, the biofuels feedstock supply will be regulated by the biofuels feedstock demand, and these together will determine the biofuels feedstock price. In addition, the biofuels price may be influenced by other factors such as societal preference or price rebate from the trading in greenhouse gas emission reductions.

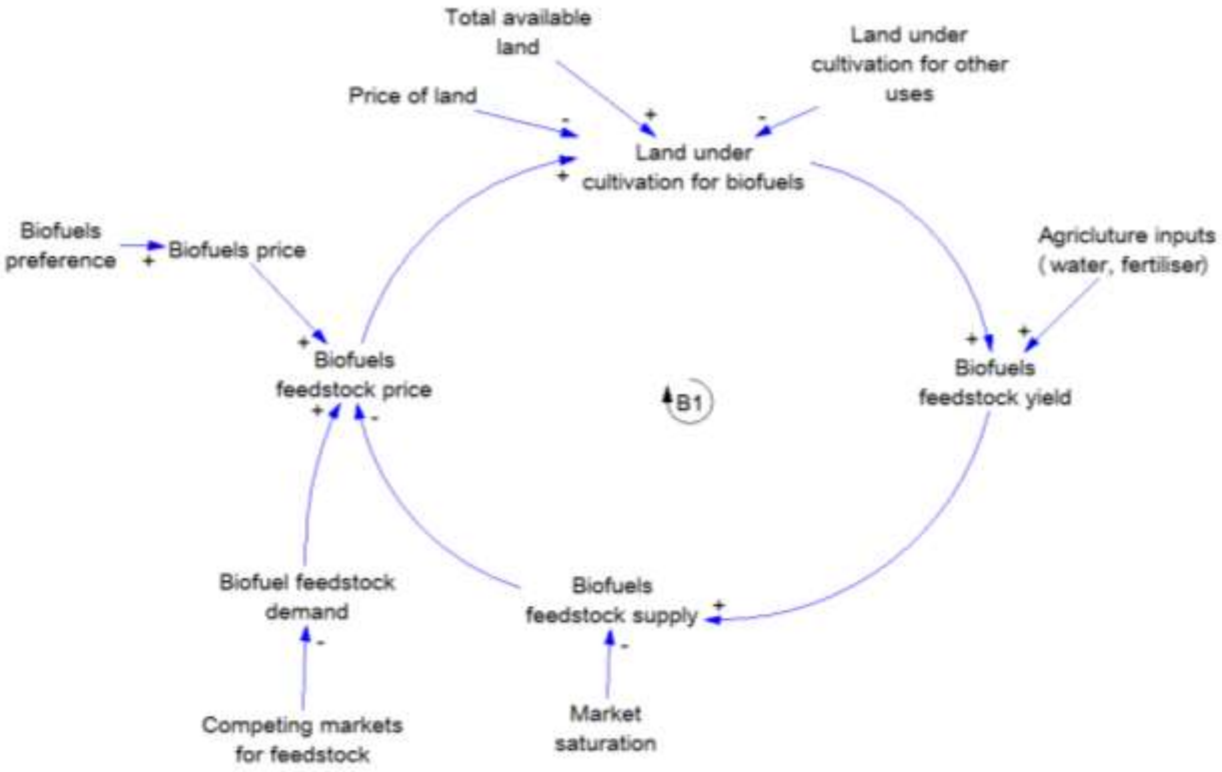

Figure 4. Biofuel feedstock production

The investment in biofuels production facilities will largely be dictated by financial feasibility. The ability to generate biofuel profits or being profitable is seen as a signal for further biofuels capital investment. As revealed in the CLD of Figure 5, these investments in turn will generally decrease in the unit cost of biofuels production, with a subsequent increase in profit and a furthering of biofuels investment and biofuels production- shown as reinforcing loop, R1. The actual biofuels profit, or profitability of the biofuels investment, will be determined by the biofuels unit price and the price of other co-products (e.g. seed cake and glycerol are co-products from biodiesel production). The biofuels capital investment will also be directed towards research and development of biofuels and therefore result in a decrease in unit costs of biofuels production, an increase in biofuel profit and an increased biofuel capital investments as shown in reinforcing loop, R2. The biofuels unit cost of production will also be influenced by the price of the biofuel feedstock as well as the availability and price of other inputs such as water fertiliser and labour.

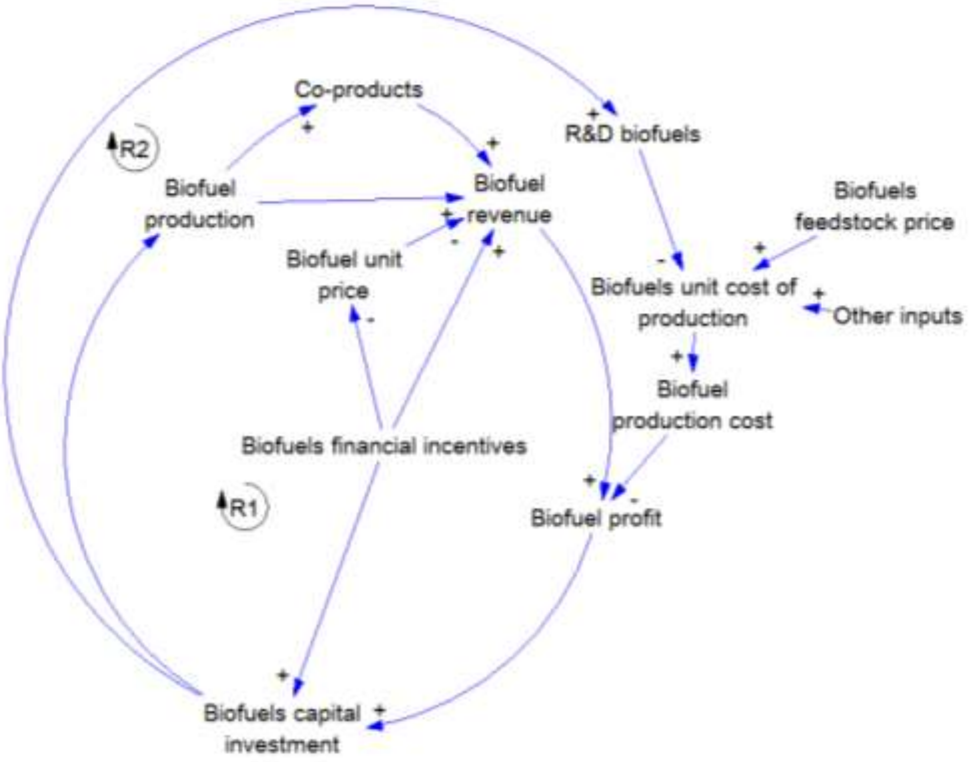

Figure 5. Biofuel investment and production

Biofuel diffusion entails market uptake through the successful biofuels distribution, storage, blending and dispensing at retail locations. The market uptake and diffusion of biofuels the predictated by the biofuels demand as shown in the CLD of Figure 6. The biofuel demand will drive the expansion biofuel retailers through influencing biofuel retail prices and biofuel retailer profits. This will lead to the expansion of biofuel retailers and an increase in biofuel supply with a subsequent decrease in the biofuel retail price; as shown by the balancing causal loop, B1. Other factors that influence the biofuels retailer profits include the biofuel wholesale price and the biofuels retailer capital investments. Further, an increase biofuels demand will result in an increased biofuels retail price and a subsequent decreasing consumer preference for biofuels; represented by the balancing loop B1. The biofuels retail price is also influenced by biofuels financial incentives (taxes, subsidies) that are in turn directed by biofuel social acceptance and the according policy and governance.

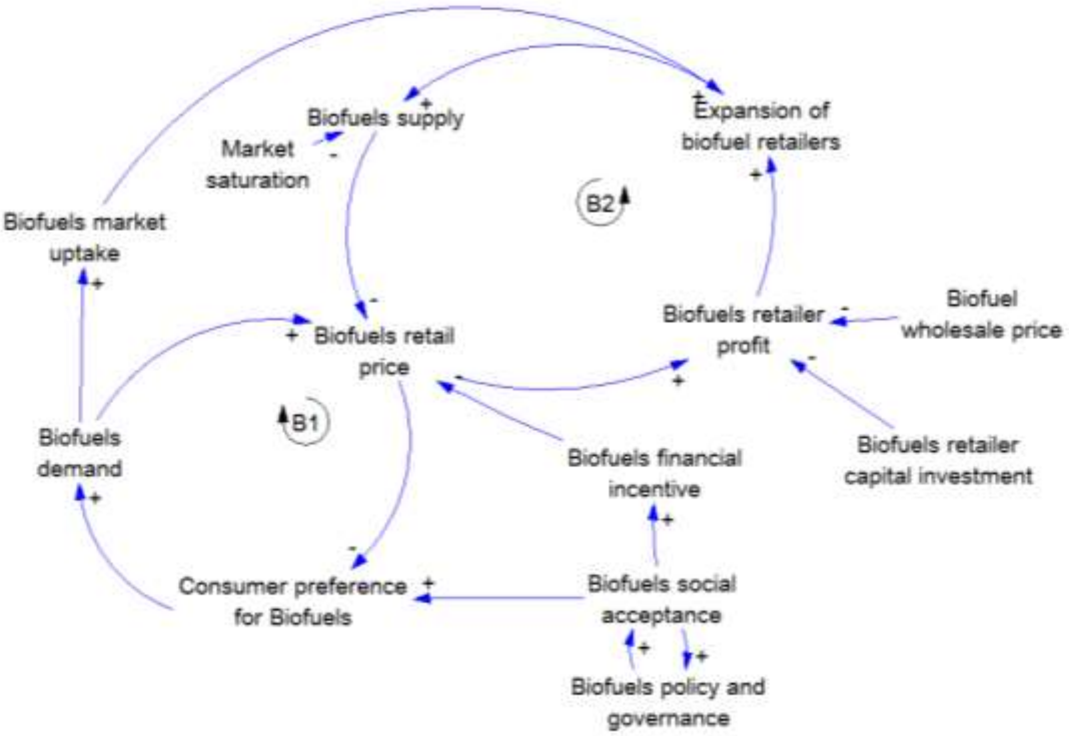

Figure 6. Biofuel market uptake and diffusion

Although the current petroleum fuel regime has known negative environmental, human-health and societal impacts; their continued use is also influenced by the existing infrastructure and *status quo*, local perceptions, risk appetite and price-sensitivity. Further, the cost competitiveness of biofuels is a very important factor that could affect the regime transition from fossil fuels to biofuels. Since a major cost component of biofuels development is the cost of feedstock, the use of wastes or appropriate biomass crop(s) is required to ensure not only financial viability, but also a ensure renewable supply of biomass that does not compromise food security. In general, biofuels are not yet economically competitive with conventional fossil fuels (i.e. gasoline and diesel), the sole exception being the Brazilian sugarcane ethanol. Thus, a biofuels green premium, the removal of incentives favouring petroleum fuels, and additional taxes or disincentives for polluting fossil fuels will be needed aid the market uptake of biofuels. However, the uptake and widespread diffusion of biofuels can also yield other benefits. By stimulating local economic development with the creation of jobs and skills in manufacturing, installation, distribution and sales, the vulnerability to external markets and shocks can be reduced so that the energy security and resilience of economy is enhanced.

4. Conclusion

Biofuels encompasses a highly heterogeneous set of socio-technical systems, involving a variety of actors across the economy. The transition to a sustainable biofuels future would require a spectrum of wide interrelated changes, which should be introduced in a coordinated and interacting systemic manner. The multi-dimensional shift from the current fossil based regime to a biofuels regime requires changes in technology, markets, policy, user practices, social and cultural preference, and governance.

A sustainable biofuels energy regime will only be fully realised if the complexities and scales of the biofuels system are understood and incorporated into effective decision-making, management and governance. The biofuels regime transition and its dynamics will be influenced by variables such as biofuels policy, user preference, cultural norms and values. Government support and policies will be needed to stimulate biofuel development and increase the market uptake and diffusion of biofuels so that they replace our current liquid petroleum fuel system. In addition to the economic viability, increased awareness and accounting of the developmental benefits of biofuels will need to be communicated in order to increase the way biofuels are valued and perceived. Considering the established petroleum dependency of the existing energy system, the transition to a biofuels future will need a coordinated and systems approach so that biofuels contribute to a new green economy and a sustainable development pathway.

Systems thinking, systems dynamics tools and a multi-level approach are useful to reveal the various factors that will influence the transition to a biofuels socio-technical system. This also allows the identification of components that will regulate the biofuels transition and behaviour of the biofuels system. An analysis of different stages of the biofuels system (biofuel feedstock production, biofuels production, and biofuels market uptake) and representation in Causal loop diagrams helps to identify influencing variables and reveal important regulating feedback loops that control the system's behaviour. This approach has also provided useful insight for decision-makers to structure and plan biofuels policies, programmes and projects so that enable low-carbon, resource efficient and socially inclusive economic growth for sustainable development.

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