A System Dynamics Approach to Understanding the Biofuels Socio-technical Transition

William Stafford[a], Thokozane Simelane[b], Martin Kaggwa[c], Shingirirai Mutanga[d]

Abstract

Biofuels are renewable energy sources that are alternatives to the current fossil fuels which dominate energy supply systems. 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, lead to increased emissions and environmental pollution, displace food security and livelihoods, and increase poverty. Therefore, appropriate management and governance will be needed to ensure that the transition towards biofuels is tailored to the local social, economic, and ecological context in order to achieve sustainable development benefits. Responding to this challenge dictates that new concepts and research tools be applied to represent and model the complex nature of biofuels systems. In addition, a multi-level perspective is needed to reveal the scale and levels of hierarchy in the system, and understand the diffusion and market uptake of biofuels. This chapter uses system dynamics tools and a multi-level approach in order to reveal the various factors that will influence the

[a] William Stafford
Natural Resources and the Environment, Council for Scientific and Industrial Research,
Corresponding author: wstafford@csir.co.za

[b] Thokozane Simelane
Human Sciences Research Council, Africa Institute of South Africa,

[c] Martin Kaggwa
Sam Tambani Research Institute

[d] Shingirirai Mutanga
Human Sciences Research Council, Africa Institute of South Africa

transition to biofuels as part of a new socio-technical system, and to identify components that will regulate the behaviour of the 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 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-ranging, interrelated changes in technology, markets, social and cultural preference, policy and governance. Due to the complexities and scale of a biofuels transition, a coordinated response from government, business and civil society will be needed support the biofuels transition and reorient development towards a green economy and sustainable development path.

5.1 Introduction

Biofuels are renewable energy fuels derived from biomass (biological matter). They include liquid, solid and gas fuels (i.e. wood-pellets, biogas, bioethanol and biodiesel) which are used to deliver energy services such as heating and cooling, electricity and transportation. The global energy system is dominated by fossil fuels (coal, petroleum and natural gas), which account for over 80 per cent of the world's total energy consumption.[1] Compared to fossil fuels, biofuels deliver a range of benefits to society; including a reduction of greenhouse gas emissions, a reduced dependency on finite fossil fuels, new opportunities for agriculture and rural development. However, if managed incorrectly, biofuel developments can cause a range of social and environmental impacts. This includes the consumption of water; the loss of soil carbon; pollution from fertilisers, pesticides and herbicides; biodiversity loss, and damage to ecosystems.[2,3,4,5,6,7,8,9,10] Furthermore, since there is a limited amount of fertile land available, the use of land for biofuels can result in the expansion of agriculture into natural areas and competition with the production of food and other valuable biomass products (food, fodder, timber, fine chemical, fibre production).[11] The sustainability of biofuel developments 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.[12,13,14] Therefore, the complex interactions between agricultural activities, local ecosystems and society require that agricultural planning and practices are well understood, integrated and effectively managed. If developed appropriately, bioenergy projects offer an opportunity for the production of renewable energy and the displacement of fossil fuels as energy sources, and also the development of more integrated and sustainable agricultural systems that are based on energy efficiency and improved natural resource management.[15,16]

Biofuels are produced from various biomass feedstocks: wood fuels, agro-fuels and various industrial and municipal wastes. Wood fuels include all types of woody biomass 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 industrial processing of agricultural products, and include agricultural crops, agricultural residues, and dedicated biofuel crops. Municipal and industrial wastes are produced by urban populations and include wastes from the residential, commercial, industrial and public sectors. The solid wastes are typically sent to landfill sites and the liquid wastes treated at wastewater treatment plants. Both of these wastes sources have a significant biomass component that can be used for bioenergy, but in many cases this opportunity is not realised.

A range of conversion technologies can be used to process biomass feedstocks into biofuels through thermochemical, physical-chemical or biochemical processes.[17] Various forms of biofuels can be produced (ethanol, biodiesel, biogas, methanol, butanol, hydrogen and synfuels), but only bioethanol, biodiesel, and biogas have been developed to a commercially mature stage and have been termed conventional or first-generation biofuels.[18] These biofuels are technologically mature and therefore can be readily adopted with relatively little risk that the technologies will not perform as expected. In addition, commercially mature biofuels, such as bioethanol, biodiesel and biogas offer current opportunities to displace fossil fuels in the market, since they can utilise the existing petroleum infrastructure and be used as a transportation fuel; either in pure form, or by blending with petroleum fuels.

There are several stages of the biofuels life cycle, such as biomass production, transportation, biofuels production, biofuels distribution to market and biofuels end use.[19] The biomass feedstock can be converted into biofuels in one of three ways: biochemical, thermochemical and physico-chemical, as shown in Figure 5.1.

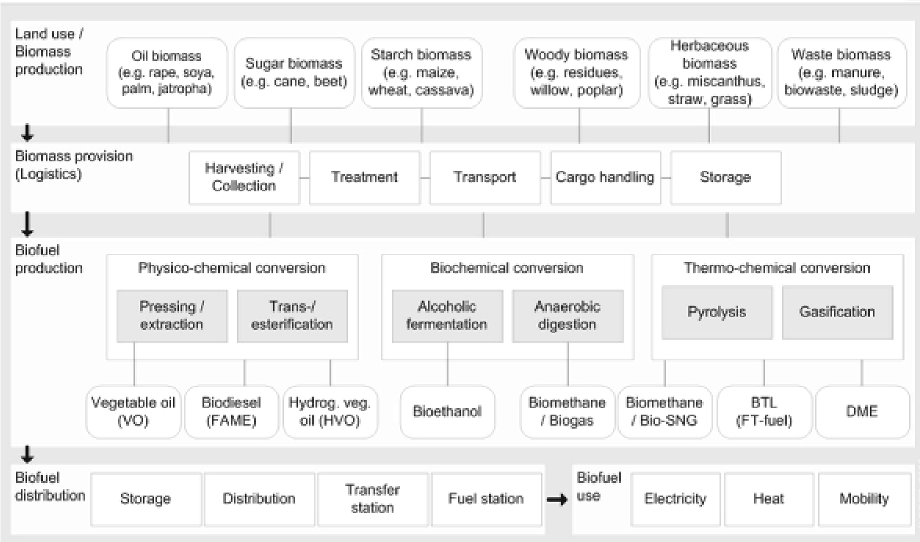

Figure 5.1 An overview of biofuels showing the stages of biomass production, biomass provisioning, biofuels production, biofuels distribution and biofuels use[20]

The transition from an energy system based on fossil fuels to one based on renewable fuels is not only driven by technology innovation and environmental concerns. The social behaviour, values and strategies of individual actors and institutions, the policies and regulations, and the infrastructure and markets will shape the widespread uptake of biofuels[21]. Understanding how energy transitions might be brought about is therefore a major transdisciplinary research challenge. Transdisciplinary research requires a multi-level perspective that views biofuels development as a socio-technical system- consisting of the scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, institutions and infrastructures. Hence, the biofuels system encompasses the production, diffusion and use of a technology that should respond to social needs and improve the well-being of the environment and society.[22,23]

5.2 Methods: Systems thinking approach to understanding the transition to biofuels

Commented [SB1]: Please ensure that this heading does not stand alone at the bottom of the page

The widespread use of renewable biofuels to replace fossil fuels is predicated on facilitating the required changes in broader social, economic and political systems. Technology uptake or adoption depends on other competing technologies, physical surroundings and context, human behaviour, cultural practices, policies and procedures. The widespread uptake of biofuels therefore involves a socio-technical transition. A socio-technical transition requires the reconfiguration and reorientation of technology research and development with, industry, markets, policy and culture to move a system to a desired future state or trajectory that is sustainable and defined by a vision "the future we want".[24] The study of socio-technical systems requires a multi-level perspective to consider a range of social, environmental and economic criteria and how they interact to help determine the behaviour of the system. This perspective enables an improved understanding in terms of technology development and adoption, by describing the complex adaptive processes that constitute the interdependencies between materials and society.[25] Biofuels fulfil socially valued functions and also condition the ways these functions are conceived and perceived. For example, the production of biogas from human and animal manures provides methane-rich biogas that can be used as a cooking fuel. Biogas adoption 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 way that waste is perceived, because human and animal manures are used as a valuable biofuel resource instead of presenting an environmental and a health burden.

The transition to biofuels on a large scale requires careful and considered strategies and plans to ensure that biofuels contribute to the green economy and a sustainable development path-characterised by lower carbon emissions, improved resource efficiency and enhanced social inclusivity.[26] Such an energy transition will face challenges of coordination and coherence across the many sectors and actors involved, as a result of the inherent system complexity and the difficulties in managing the transition. A lack of planning and co-ordination may lead to negative impacts – 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.[27,28] In this study, a systems thinking approach was used to facilitate the understanding of the biofuel socio-technical transition.[29] Systems comprise interdependent groups of elements forming a unified pattern. Systems thinking requires a departure from examining isolated events and their causes, to the examination of whole systems comprising of inter-connected and interacting parts. This approach to the biofuels transition reveals the complex, multi-scale, adaptive and emergent properties of a biofuels transition and can thereby help incorporate sustainability into development decisions.[30]

Systems thinking and causal loop diagrams (CLDs) are used to capture and investigate the interrelationships between heterogeneous individuals, groups, institutions and networks, as well as variables such as policy, technology, resources, and infrastructure. CLDs display the causal interactions or relationships and their polarity, and often reveal feedback loops that help to regulate the system's behaviour. The feedbacks that regulate the system's behaviours and offer opportunity for control and management.[31] A positive, or reinforcing, feedback loop reinforces change, often at an ever-increasing rate. The rate of change may appear to be minor during the early stages of positive feedback, but the change becomes magnified through reinforcing effects, to reach significant proportions. A negative, or balancing, feedback loop imposes regulating or stabilising 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). Since many of these effects will occur with different time scales (and some may occur after a considerable delay), the response and overall behaviour of the system will be determined by the dynamics of the interactions. CLDs increase our understanding of cause-and-effect and the consequences of certain actions, thereby offering insights into system behaviour.. CLDs are therefore valuable tools for decision makers and offer new opportunities to regulate, manage and control the system.

5.3 Results and discussion: Analysis of the biofuels transition

Commented [SB2]: Please ensure that this heading does not stand alone at the bottom of a page

The recent global climate change, food and economic crises have urged a reorientation of the economy to a low-carbon, resource-efficient and socially inclusive development path. This global landscape and the green economy[32] are influencing the development agenda and the biofuels transition. The transition to a biofuels socio-technical system requires an appropriate regime with enabling and supportive policy and governance to increases the awareness, uptake and diffusion of renewable energy and biofuels.[33,34] Since biofuels are currently in their infancy in Africa, the policy support and biofuels market will need to be developed;

with support for niche biofuels developments and enabling the diffusion and uptake of biofuels until they become the prevailing socio-technical regime that completely displaces carbon-intensive petroleum fuels. Achieving biofuels technology uptake and diffusion will require strong support in terms of governance, fiscal incentives and appropriate policies, so that biofuels are competitive with petroleum fuels in terms of market price and economic viability. The wide-scale adoption of biofuels 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, and refilling stations). In addition, there will need to be awareness and communication of the biofuel technology innovation and its perceived advantages, so that society may value biofuels beyond the competitive price set by current petroleum fuels – and thereby positively influence their value function.[2222,35]

Formatted: Endnote Reference

5.3.1 Identifying the biofuels socio-technical landscape, regime 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.[3434,36] In such a system, technical and social elements are co-constitutive, interacting and shaping each other with exchanges in both directions.[37]

Formatted: Endnote Reference

It follows, therefore, that biofuels are not just a series of engineered parts which ultimately perform an energy conversion. The biofuels system also entails the configuration of social, economic, technological and governance aspects of development; and may have emerged contingently in particular contexts and mirror the wider global governance and policy. For example, the need to mitigate climate change and adopt renewable energy, such as biofuels, has resulted not only from policy response and climate governance by responsible governments, but also from the market forces of human individuals and groups with pro-environmental behaviour that demands renewable energy and other green goods and services.[38] These individuals and groups have various roles, responsibilities, norms and perceptions, which in turn shape the socio-ecological system to influence the wide-scale adoption of biofuels.

Transitions of socio-technical regimes are considered to be complex, long-term processes usually instigated in niches[23]. Whether intended or not, the multitude of actors involved in niches makes their evolution 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 5.2). These levels are described below.

Formatted: Endnote Reference

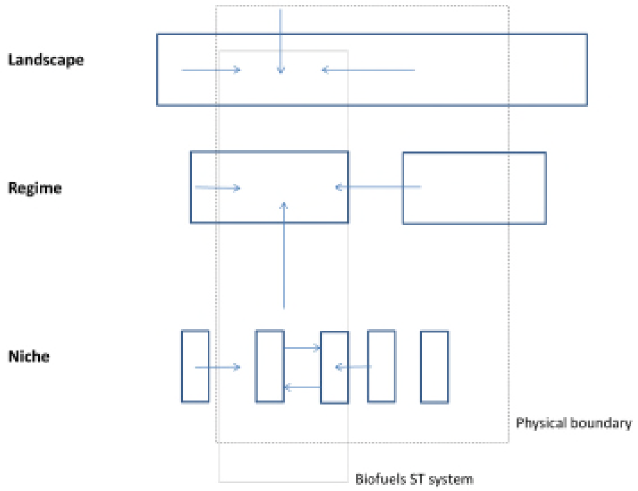

Figure 5.2 The multi-level level perspective of a socio-technological system.[39] The biofuel regime will have a defined socio-technical system boundary that does not necessarily coincide with a physical boundary. Arrows indicate the desired transition to the biofuels socio-technical (ST) system.

5.3.1.1 Landscape

The biofuels landscape lies at macro-level. Developments at the landscape level are largely external to developments in the regime and niches, but do influence them. Examples include material infrastructure, institutional factors, social values, beliefs, politics and culture.[40] For biofuels developments, the existing landscape can be broadly be described by the current 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; a growing acknowledgment of the key role that agriculture plays in development; and the renewed interest in low-carbon economic growth and the green economy offering a pathway to sustainable development.[32]~~[32]~~

Formatted: Endnote Reference

5.3.1.2 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.[41] 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. Fiscal incentives (eco-taxes, incentive payments/subsidies, eco-labelling, and environmental markets) may be needed to reorient the existing regime by adjusting the market to better account for the sustainability benefits of biofuels.

Given the contextual nature of biofuel developments, there is a need for 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 required to control and regulate the quality of biofuels to ensure that performance and warranty on engines are not compromised; and thereby gain market acceptance. These requirements could place additional costs on vehicle owners, resulting in resistance to the adoption of biofuels.

5.3.1.3 Niche

Commented [SB3]: Please ensure that this heading does not stand alone at the bottom of a page

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 areas 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 that change the structure and function of a social system.[22]~~[22]~~ Niche markets can only truly develop and flourish if supported by

Formatted: Endnote Reference

changes in government mechanisms and the existing regime. In many developing countries, such as South Africa, the lack of investment capital, fiscal incentives and policies supporting biofuels has hampered development. South Africa could take the lessons learnt from 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 various concerns that the industrial agriculture model adopted by Brazil has marginalised resource-poor farmers, who depend on a multitude of agricultural and forest products for their livelihoods (food, fuel, medicine, building materials).[1818,42]

Formatted: Endnote Reference

5.3.2 Causal loop diagrams to represent the biofuels transition

CLDs are a tool used in system dynamics (SD) to identify and explore the relationships and effects between components of a system. The interactions between elements of the system cause system behaviour, and can create emergent properties that cannot be described or predicted when looking at elements in isolation. A CLD creates a conceptual understanding of how changes in important variables will influence 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 '+') or change in the opposite direction (indicated with a '–'). Processes that have feedback in the same direction are called reinforcing processes (indicated with 'R') since they amplify the effect. Similarly, processes that have feedback to give a change in the opposite direction are balancing (indicated with 'B') and negate or dampen out the effect. Using this approach, a CLD which captures major aspects of biofuel production was developed (Figure 5.3).

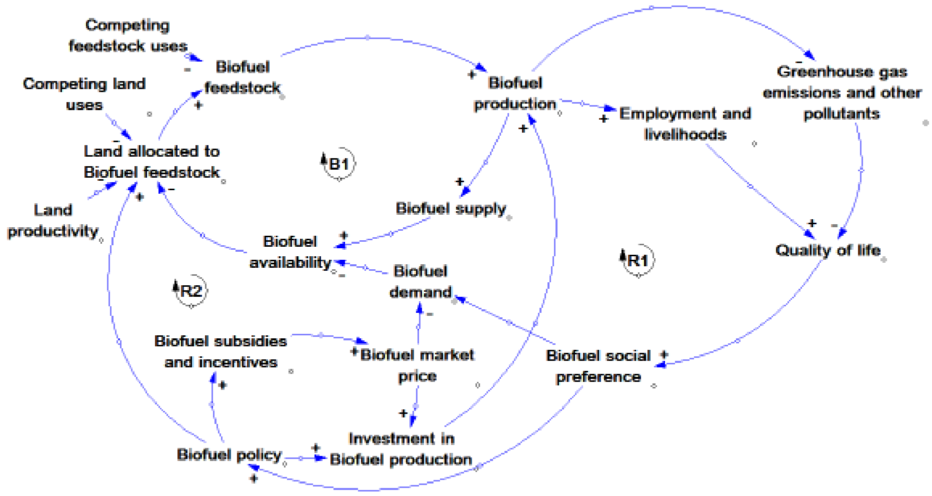

Figure 5.3 General CLD of the biofuel system

The global and national policies and incentives that support renewable energy and biofuel development will increase the land allocated to the production of biofuel feedstock and the production of biofuels. Increased biofuels production will improve human well-being through the reduction of emission of greenhouse gases and other pollutants, as well as providing new opportunities for employment and improving livelihoods. These improvements in human well-being and quality of life will increases the social preference for biofuels; which will stimulate the biofuel demand and thereby increase biofuel production. This reinforcing loop of increasing biofuel production, is represented by R1. Another reinforcing loop, R2, similarly shows that the biofuels social preference will influence biofuel policy to provide incentives for increasing biofuel production. The consequent reductions in greenhouse gas emissions and improvements in employment and livelihoods (attributed to the production and use of biofuels), will stimulate an increase in biofuel production. Although, biofuel production and demand will largely be a reflection of the biofuel market price, it will be positively influenced by biofuel subsidies, incentives and biofuel social preference. There will be also factors limiting an ever-increasing supply of biofuels. The reinforcing effects that increase biofuel production is constrained by a balancing effect, B1, that occurs when the biofuel supply exceeds demand, resulting in more biofuel available on the market (market saturation) and less land allocated to biofuel production. In addition, other factors will affect the amount of land allocated to biofuel feedstock production; such as the biofuel crop type, competing land uses, and alternatives uses for the biofuels feedstock (competition with the production of food, fodder, timber, fibre and fine chemicals). There is threat that biofuels will reduce food security since both biofuels and food production compete for arable land and other the agricultural inputs of water, soil carbon and fertiliser. This competition may cause an increase global food prices; such as the 30 per cent increase in grain price from 2000 to 2007 and the 20 per cent increase price of vegetable oil price in 2014 that has been associated with the increased market demand from biofuels blending mandates.[43,44] The land available for biofuels will also be constrained by the need to conserve biodiversity in order to ensure the provision of ecosystem services, on which human livelihoods depend. This is particularly relevant in developing countries such as Africa, where most of the population live in rural areas and depend on natural resources for their livelihoods, but have customary land rights and are not land owners with legal tenure.[45,46,47]

The biofuels socio-technical system can be explored in greater depth by analysing the stages of the biofuels life cycle – biofuel feedstock production, biofuels production, and biofuels market uptake. The CLD developed for biofuel feedstock production, Figure 5.4, reveals that the biofuel feedstock market price will determine the allocation of land for the cultivation of biofuel feedstocks. Other important external variables that determine the land available for biofuels production include the price of land, the land currently under cultivation for other agriculture and forestry products, and the total land area that can be cultivated whilst ensuring the conservation of biodiversity and ecosystems. Given positive market prices and signals, the land area under cultivation for biofuels and associated agriculture inputs will increase to yield more biofuel feedstock. The increase in biofuels feedstock supply will reduce the feedstock price, which will reduce the amount of land allocated to biofuel feedstock production. This self-regulating balancing loop of biofuels feedstock supply is shown as B1. In addition, the biofuels feedstock supply will be regulated by the biofuels feedstock demand, since the supply and demand together determines the biofuels feedstock price. Increasing biofuels feedstock supply will reach market saturation so that the biofuel feedstock demand is reduced, causing a reduction in biofuel feedstock price and a reduction in land area under cultivation for biofuels– represented by the balancing loop, B2. Furthermore, the biofuels feedstock demand and price will be influenced by other factors that influence the preference for biofuels; such as biofuels price and the competing markets for biofuels feedstock.

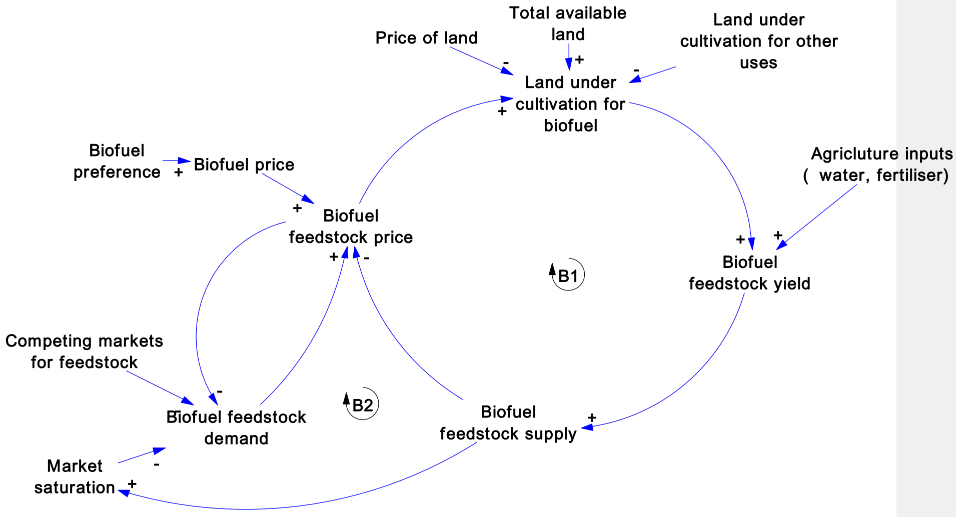

Figure 5.4 Biofuels feedstock production

The investment in biofuels production facilities will largely be dictated by financial feasibility; since the ability to generate biofuel profits, or being profitable, is seen as a signal for further biofuels investment. As revealed in the CLD in Figure 5.5, these investments in turn will generally decrease the unit cost of biofuels production, with a subsequent increase in profit and a furthering of biofuels investment and biofuels production –shown by the reinforcing loop, R1. The actual biofuels profit, or return on investment, will be determined by the biofuels unit price and the price of other co-products (e.g. seed cake and glycerol co-products from biodiesel production); and there is growing trend in the development of biorefineries that produce a spectrum of products from the biomass resource.[48] The biofuels capital investment that is directed towards research and development of biofuels is likely to result in a decrease in unit cost of biofuels production, an increase in biofuel profit, and an increase in biofuel capital investments – as shown in the 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.

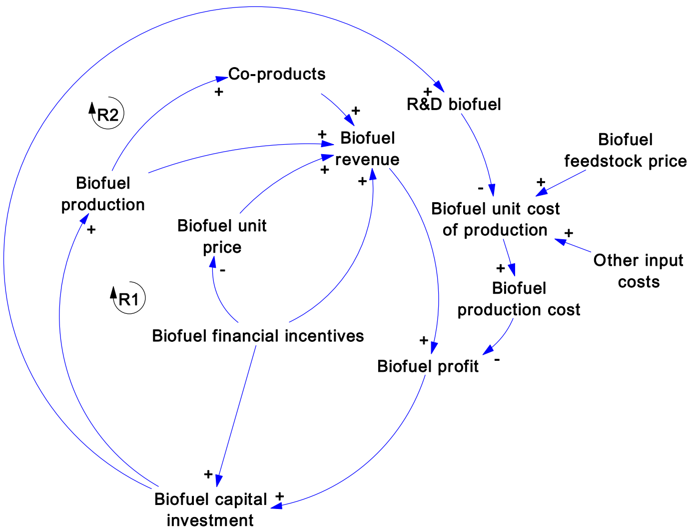

Figure 5.5 Biofuels production

Biofuels diffusion entails market uptake and the successful distribution, storage, blending and dispensing of biofuels at retail locations. The market uptake and diffusion of biofuels are predicated by the biofuels demand, as shown in the CLD of Figure 5.6. An increase in demand for biofuels will result in an increase in biofuels retail price and a subsequent decrease in in consumer preference for biofuels and a reduced demand – as represented by the balancing loop, B1. Similarly, the increased demand for biofuels will result in an increased market uptake, the expansion of biofuel retailers and increased biofuel supply until market saturation is reached, which will reduce the biofuel demand as shown in the balancing loop, B2. The biofuel demand will also drive the expansion of biofuel retailers through influencing biofuel retail prices and biofuel retailer profits, resulting in an expansion of biofuel retailers, an increase in biofuel supply and a decrease in biofuel retail price that will reduce the further expansion of biofuels – represented by the balancing loop, B3. The biofuels retail prices will also be influenced by biofuels social acceptance and supporting policy and governance that influence market prices by providing a green premium or financial incentive for biofuels.

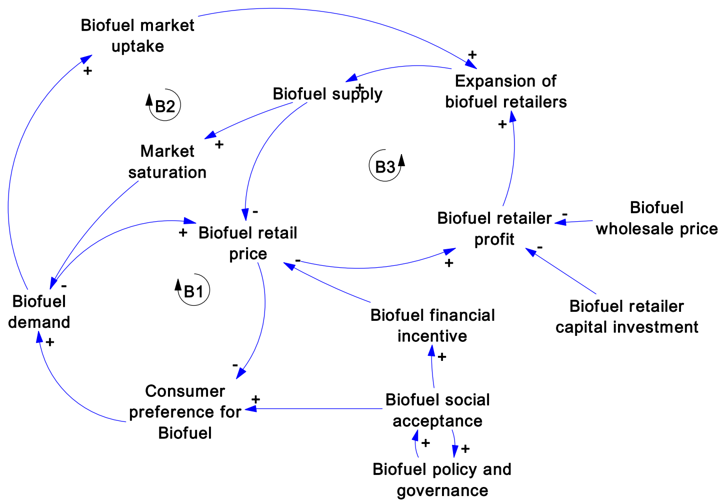

Figure 5.6 Biofuels diffusion and market uptake

The cost competitiveness of biofuels is a very important factor that could affect the regime transition from fossil fuels to biofuels. Although the current fossil fuels regime has known negative environmental, human-health and societal impacts whose costs are largely externalised, their continued use is also influenced by the existing infrastructure and status quo, local perceptions, risk appetite and price sensitivity. Since a major cost component of biofuels is the cost of feedstock, the use of wastes or appropriate energy crop(s) can ensure financial viability and the renewable supply of feedstock that does not compromise food security. In general, biofuels are not yet economically competitive with liquid petroleum fuels. Incentives to account for the benefits of biofuels and the removal of current incentives favouring petroleum fuels will be needed to support the development and market uptake of biofuels.

5.4 Conclusion

Biofuels encompass a highly heterogeneous set of socio-technical systems involving a variety of actors in the economy. The transition to a sustainable biofuels future will require the coordination of a wide spectrum of interrelated changes in order to shift from the current fossil fuels based system to a biofuels one. These multi-level changes involve the reconfiguration of technology, markets, social and cultural preference, policy and governance.

.

A multi-level approach that involves systems thinking and system dynamics tools provides useful insight into complexities and scale, and helps reveal the various factors that will influence the transition to a sustainable biofuels system. . An analysis of different stages of the biofuels system (biofuel feedstock production, biofuels production, and biofuels market uptake) and their representation in causal loop diagrams helps to identify influencing variables and reveal important regulating feedback loops that control the system's behaviour. This enables the identification of components that will control and regulate the behaviour of the system and offers opportunities to manage the biofuels socio-technical transition. Although biofuels are not yet economically competitive with liquid petroleum fuels, market prices poorly reflect the value that biofuels can bring to society. These benefits include the generation of renewable energy that improves energy availability and access in rural areas, enhancing national energy security, and reducing the emission of greenhouse gases and other environmental pollutants. Furthermore, since energy powers the economy through a range of services (transportation, space heating/cooling, cooking/chilling and electricity); a regime shift from fossil fuels to biofuels can drive low-carbon, resource-efficient and socially inclusive economic growth. The biofuels transition and its dynamics will be strongly influenced by biofuels policy, market mechanisms, user preference, cultural norms and values. Considering the established dependency on fossil fuels, the biofuels transition will require increased government support from fiscal incentives (eco-taxes, incentive payments/subsidies, eco-labelling, and environmental markets) and an improved awareness of the benefits that biofuels can bring to society, so that their value can be better incorporated into market prices. A coordinated and systemic approach from government, business and civil society will be needed support the biofuels transition and reorient development towards a green economy and sustainable development path.

Notes and references

[1] Worldwatch Institute, 2007. *Fossil fuels dominate primary energy consumption*. Available at: http://www.worldwatch.org/fossil-fuels-dominate-primary-energy-consumption-1 [Accessed 2 December 2015].

[2] Duxbury, J.M., 1994. The significance of agricultural sources of greenhouse gasses. *Nutrient Cycling in Agroecosystems,* 38(2), pp.151–163.

[3] Intergovernmental Panel on Climate Change (IPCC), 2007. Climate change: Working Group I: The physical science basis. IPCC Fourth Assessment Report: Climate Change. Available at: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-1-1.html [Accessed 20 February 2011].

[4] Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. and Sirotenko, O., 2007. Agriculture. Climate Change 2007: Mitigation. Metz, B., Davidson, O.R., Bosch, P.R., Dave R. and Meyer, L.A. (eds). Cambridge and New York: Cambridge University Press.

[5] Adler, P.R., Del Grosso, S.J. and Parton, W.J., 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. *Ecological Applications*, 17, pp.675–69.

[6] Jordan, N., Boody, G., Broussard, W., Glover, J.D., Keeney, D., McCown, B.H., McIsaac, G., Muller, M., Murray, H., Neal, J., Pansing, C., Turner, R.E., Warner, K. and Wyse, D., 2007. Environment: Sustainable development of the agricultural bio-economy. *Science*, 316, pp. 1570–1571.

[7] Stone, K.C., Hunt, P.G., Cantrell, K.B. and Ro, K.S., 2010. The potential impacts of biomass feedstock production on water resource availability. *Bioresource Technology*, 101, pp.2014–2025.

[8] Browne, P., 2009. Tanzania suspends biofuel investments. Available at: *Green Inc. Blog* http://greeninc.blogs.nytimes.com/2009/10/14/tanzania-suspends-biofuels-investments/ [Accessed 15 August 2016].

[9] Nnanna, G., 2011. Addressing the food versus fuel debate in Ghana. The Ghanaian Journal. Available at: http://www.theghanaianjournal.com/2010/02/08/addressing-the-food-versus-fuel-debate-in-ghana/ [Accessed 15 August 2016].

[10] Koh, L.P. and Wilcove, D.S., 2008. Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters,* 1(2):60–64.

[11] Von Maltitz, G.; Stafford, W., 2011. Assessing opportunities and constraints for biofuel development in sub-Saharan Africa. Center for International Forestry Research. Working Paper 58. Bogor, Indonesia. Available at:

http://www.cifor.org/publications/pdf_files/WPapers/WP58CIFOR.pdf [Accessed 15 August 2016].

[12] Robertson, G.P., Dale, V.H. and Doering, O.C., 2008. Agriculture: Sustainable biofuels redux. *Science*, 322(589), pp.49–50.

[13] Scharlemann, J.P.W. and Laurance, W.F., 2008. Environmental science: How green are biofuels? *Science*, 319, pp.43–44.

[14] Kline, K., Dale, V.H., Lee, R. and Leiby, P., 2009. In defence of biofuels, done right. *Issues in Science and Technology*, 25, pp.75–84.

[15] De Vries, S.C., Van de Ven, G.W.J., Van Ittersum, M.K. and Giller, K.E., 2010. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy*, 34, pp.588–601.

[16] International Assessment of Agricultural Science and Technology for Development (IAASTD) Project. IAASTD Global report. Washington, DC: World Bank. Available at: http://documents.worldbank.org/curated/en/753791468314375364/pdf/354480rev0pdf.pdf [Accessed 20 July 2017].

[17] Jumbe, C.B.L., Msiska, F.B.M. and Madjera, M., 2009. Biofuels development in Sub-Saharan Africa: Are the policies conducive? *Energy Policy*, 37, pp. 4980–4986.

[18] International Energy Agency (IEA), 2011. Technology roadmap*:* Biofuels for transport. Available at: http://www.iea.org/publications/freepublications/publication/biofuels_roadmap_web.pdf [Accessed 20 July 2017].

[19] Halog, A., Manik, Y., 2011. Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment. *Sustainability*, 3, pp. 469–499. ISSN 2071-1050. Available at: http://www.systemdynamics.org/conferences/2008/proceed/papers/PAPAC428.pdf [Accessed 20 July 2017].

[20] Perimenis, A., Walimwipi, H., Zinoviev, S., Muller-Langer, F. and Miertus, S., 2011. Development of a decision support tool for the assessment of biofuels. *Energy Policy*, 39, pp.1782–1793.

[21] Amigun, B., Kaggwa, M., Musango, J., Mutanga S., Simalane T. and Stafford, W., 2011 Africa's technology options for renewable energy production and distribution energy transition in Africa. Chapter 6: Energy transition in Africa. Pretoria: Africa Institute of South Africa.

[22] Geels, F., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, 31, pp.1257–1274.

[23] Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy*, 33(6-7), pp.897–920.

[24] World Commission on Environment and Development 1987. Chapter 2: Towards Sustainable Development. Our Common Future. United Nations documents. A/42/427.

[25] Russell, S. and Williams, R., 2002. Social shaping of technology: Frameworks, findings and implications for policy with glossary of social shaping concepts. In Sørensen, K.H., Williams, R. and Aldershot, E.E. (eds): Shaping Technology, Guiding Policy: Concepts, Spaces and Tools, pp.37-132. Edward Elgar, Aldershot.

[26] Amigun, B., Musango, J. and Stafford, W., 2011. Biofuels and Sustainability in Africa. *Renewable and Sustainable Energy Reviews*, 15, pp.1360–1372.

[27] Upham, P., Thornley, P., Tomei, J. and Boucher, P., 2009. Substitutable biodiesel feedstocks for the UK: A review of sustainability issues. *Journal of Cleaner Production*, 17 (1), pp.S37–S45.

[28] Tomei, J. and Upham, P., 2009. Argentinean soy based biodiesel: An introduction to production and impacts. *Energy Policy*, 37(10), pp.3890–3898.

[29] Sterman, J.D., 2002. All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review*, 18(4), pp.501–531.

[30] Smith, A. and Stirling, A., 2007. Moving outside or inside? Objectification and reflexivity in the governance of sociotechnical systems. *Journal of Environmental Policy and Planning*, 9(3-4), pp.351–373.

[31] Goodman, Michael R., 1989. Study Notes in System Dynamics. Waltham, MA: Pegasus Communications.

[32] United Nations Environment Programme (UNEP) 2011. Towards a green economy: Pathways to sustainable development and poverty eradication. Available at: https://www.unep.org/greeneconomy/sites/unep.org.greeneconomy/files/field/image/green_economyreport_final_dec2011.pdf [Accessed 15 August 2016].

[33] Smith, A., Stirling, A. and Berkhout, F., 2005. The governance of sustainable socio-technical transitions. *Research Policy*, 34, pp.1491–1510.

[34] Elzen, B. and Wieczorek, A., 2005. Transitions towards sustainability through systems innovation. *Technological Forecasting and Social Change*, 72, pp.651–661.

[35] Rogers, M.E., 2003. The diffusion of innovations. London: Free Press, A Division of Macmillan Publishing Co. Inc.

[36] Bijker, W.E., Hughes, T.P. and Pinch, T. (eds), 1987. The social construction of technological systems. Cambridge: MIT Press.

[37] Bijker, W.E and Law, J. (eds), 1992. Shaping technology/building society: Studies in sociotechnical change. London: MIT Press.

[38] Rip, A., Kemp, R.P.M. and Kemp, R., 1998. Technological change. In: Rayner, S. and Malone, E.L. (eds), Human choice and climate change. Vol. II. *Resources and Technology*, pp.327–399, Columbus, Ohio: Battelle Press.

[39] Salé, A.C. and Dewes, H., 2009. Opportunities and challenges for the international trade of jatropha curcas-derived biofuel from developing countries. *African Journal of Biotechnology*, 8(4), pp.515–523.

[40] Geels, F.W. and Kemp, R., 2006. Transitions, transformations and reproduction: Dynamics in socio-technical systems. In: McKelvey, M. and Holmen, M. (eds). Flexibility and stability in the innovating economy. Oxford: Oxford University Press, pp.227–256.

[41] Lane, B., 2002. Optimising implementation strategies for fuel cell powered road transport systems in the United Kingdom. PhD Thesis. The Open University, Milton Keynes.

[42] Smeets, E., Junginger, M., Faaij, A., Walter, A. and Dolzan, P., 2008. Sustainability of Brazilian bio-ethanol. Energy Efficiency and Conservation Authority *(EECA).* Report 8. Available at: https://www.bioenergy.org.nz/documents/resource/LB-sustainability-brazilian-sugarcane-report-08.pdf [Accessed 15 July 2016].

[43] Rosegrant, M.W., 2008. Biofuels and grain prices: Impacts and policy responses. Testimony for the U.S. Senate Committee on Homeland Security and Governmental Affairs. Washington, DC: International Food Policy Research Institute.

[44] Abbott, P., 2009. Development Dimensions of High Food Prices. *OECD* Food, Agriculture and Fisheries Working Papers. No. 18, OECD Publishing. doi: 10.1787/222521043712.

[45] German, L., Schoneveld, G.C. and Gumbo, D., 2011. The local social and environmental impacts of smallholder-based biofuel investments in Zambia. *Ecology and Society*, 16(4), p.12.

[46] Schoneveld, G.C., German, L.A. and Nutakor, E., 2011. Land-based investments for rural development? A grounded analysis of the local impacts of biofuel feedstock plantations in Ghana. *Ecology and Society*, 16(4), p.10.

[47] Walter, A., Dolan, P., Quilodran, O., Garcia, J., Silva, C., Piacente, F. and Segerstedt, A., 2008. A sustainability analysis of the Brazilian ethanol. Campinas: UNICAMP.
[48] Taylor, G., 2008. Biofuels and the biorefinery concept. *Energy Policy*. 36(12), pp.4406–4409.