Renewable and Sustainable Energy Reviews 82 (2018) 247–259

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainable and renewable energy supply chain: A system dynamics overview

M. Ricardo Saavedra M.[a,*], Cristiano Hora de O. Fontes[b], Francisco Gaudêncio M. Freires[b]

[a] Graduate Program in Industrial Engineering (PEI), Federal University of Bahia, Salvador 40210-630, Brazil
[b] Department of Chemical Engineering, Federal University of Bahia, Salvador 40210-630, Brazil

ARTICLE INFO

Keywords:
Renewable energy
Supply chain
System dynamics
Sustainable supply chain
Modelling

ABSTRACT

Renewable Energy and Sustainable Supply Chain Management have been extensively studied over the last decade. However, techniques based on the modelling and simulations have not been applied extensively in the supply chain of renewable energy. The main purpose of this study is to identify the latest System Dynamics contributions and trends related to the supply chain of renewable energy. An overview of works published in several journals and related to the application of the System Dynamics approach in Renewable Energy Supply Chain (RESC) is provided. Only 10 papers focusing on the application of system dynamics in RESC were found and these were classified into three groups of analysis. Although the literature is scarce, this work shows the importance of system modelling considering: (i) improving the understanding of supply chain in renewable energy and (ii) developing modelling and simulation approaches in renewable energy systems. This paper represents a source for elaborating a System Dynamics framework applied on RESC and provides a comprehensive bibliography of papers published in the last decade.

1. Introduction

Renewable energy (RE) and sustainable supply chain management (SSCM) play an important role in the literature considering its contribution and significance in the global energy industry. Firstly, SSCM has been studied in depth in order to establish concepts associated with the sustainability of supply chain, e.g. [1,2]. Secondly, RE has been an important issue in the green economy as the use of fossil fuels has been declining because of its greenhouse gas (GHG) emissions and low prices, e.g. [3]. To address complexity in decision-making processes, some practitioners and researchers have used system dynamics (SD) as a method for modelling and simulating complex situations to recognise changes, multiple players and interdependencies among different systems and processes [4].

Two of the main objectives in SSCM are the performance assessment and integration of the operations associated with environmental, social and economic issues, e.g. [1,5,6]. This integration cannot cope with a sustainable approach and in the energy sector in particular, this could have a meaningful impact on economic development [7]. A sustainable supply chain (SSC) must involve coordination among resources, flows and stocks with a well-defined sustainability concept and this requires more attention by all actors involved in the renewable energy value chain.

Some literature reviews focusing on the modelling of SSCM have shown how to reduce costs by using operational research methods [5,8,9]. On the other hand, the most used method for the analysis of RE is Life-Cycle Assessment (LCA) [3,10]. LCA has been considered the most comprehensive approach for environmental impact assessment as well as an important tool for decision makers to establish the investment strategy in the renewable energy field [3,10]. Likewise, this tool has been used in the environmental evaluation of buildings in order to design and construct low energy buildings with less environmental impact [11]. However, this approach is considered insufficient to understand the dynamic interrelationships between subsystems because it requires complementary approaches for assessing the economic and social dimensions of sustainability, i.e. Triple-Bottom-Line [10].

The use of different approaches to understanding complex RESC systems has created a need to develop integrated frameworks to reduce uncertainty. Some problems related to the level of complexity of multiple interactions involving economic, environmental and social elements as well as critical components such as performance and cost assessing have not been dealt with by traditional methods based on operational research models [10,12]. Therefore, perhaps these problems could be better addressed by using simulation and modelling-based approaches for a better understanding of the renewable energy supply chain system.

* Corresponding author.
E-mail address: ricardo.saavedra1@gmail.com (M.R. Saavedra M.).

http://dx.doi.org/10.1016/j.rser.2017.09.033
Received 25 March 2017; Received in revised form 28 June 2017; Accepted 14 September 2017
1364-0321/

Among the methods based on modelling and simulation, Agent-Based Modelling (ABM), Discrete Event Simulation (DES) and System Dynamics Approach (SDA) are the most applied [13]. The SDA adopts a top-down approach, coping with a complex system at a more aggregate level and modelling the interrelationships between sub-systems in order to analyse the specific overall system behaviour [4,14]. Few works have shown the potential of applying the System Dynamics Approach (SDA) in the Renewable Energy Supply Chain (RESC). This paper focuses on the application of SDA in RESC, identifying its main contributions, assumptions, limitations and opportunities for current and future works proposing a simulation and modelling-based framework as a method for implementing the SDA.

System Dynamics is considered a powerful method for describing and analysing the relationships between factors in complex systems to simulate system behaviour over time [15]. It has been used to understand and assess the impacts of variables in renewable energy systems as well as a decision support method in different sectors. A recent review [16] summarized the latest system dynamics trends related to the energy sector in four main topics: Fossil Fuels, Renewable Energy, Electricity and Further energy-related resources. However, the main outcomes related to the Renewable Energy showed that SD has been applied in specific topics such as market behaviour, bio economy, energy policies and CO_2 emissions, and there has been no work involving the supply chain of renewable energy.

This paper presents an overview of the literature on system dynamics modelling applied in renewable energy supply chain, considering works published between 2007 and 2017. Although the literature is scarce, this work shows the importance of system modelling considering: (i) improving the understanding of supply chain in renewable energy and (ii) developing modelling and simulation approaches in renewable energy systems. This study represents a novelty in the analysis of the supply chain in renewable energy using SD, highlighting that this approach provides harmony between its subsystems and processes, understanding the system behaviour, testing policies for improvement, and assessing impacts over time [17]. In contrast to works focusing on mathematical models rather than on simulation [18,19], the use of SDA on design and modelling of the bioenergy supply chain provides a new perspective that involves the analysis of the whole-system dynamic [20].

This work shows that the application of SDA in RESC poses challenges and unresolved issues which can be grouped into three main aspects. First, the Biomass Scenario Model (BSM), which was created to evaluate the biomass-to-biofuels supply chain and was applied in four different studies [12,21–23]. For instance, by using a system dynamics model, the BSM has demonstrated the need for substantial policy intervention and the importance of coordinating investment, land use expansion and incentive management [12,21]. Second, the Scenario Analysis Process is frequently used in SD models however, it is not used as a forecasting tool which requires another alternative to complement the simulation methods. In contrast to the optimisation model, sensitivity analysis is a powerful method for improving the decision maker's knowledge and understanding of the system behaviour by analysing different scenarios in a variety of contexts [24–27]. The scenario analysis technique is able to determine the most significant factors affecting the overall performance of the supply chain model. Finally, the Hybrid Modelling Framework integrates multiple tools to assess complex system problems, e.g. different actors in the supply chain with different needs, objectives and decision-making behaviours, which present additional challenges for the sustainable supply chain of biofuel systems [10,28]. Although there is a need to integrate a methodological framework in order to represent the reality of supply chains and generate alternative solutions to improve their performance, the Hybrid Modelling Framework is not as widely used as dynamics simulation [29].

A few authors have highlighted at least two or three works applying system dynamics [8]. On the other hand, Supply Chain Management (SCM) has had an important role in the biomass supply chains, e.g. [30]. The lack of significant literature on system dynamics applications suggests that confidence in this approach (SD) has not yet been consolidated and their potentialities have not been effectively highlighted. For instance, SD can be applied to assist the long-term strategies analysis in decision-making by quantifying the anticipated effects of choices of strategic alternatives [31].

This paper is divided into five sections. A brief review and discussion of the topics on Renewable Energy Supply Chain, Sustainable Supply Chain Management and System Dynamics Approach are presented in Section 2. Section 3 presents the method adopted to select the references and organize them according to the focus on the application of system dynamics in the supply chain of renewable energy. Both the main RESC and SD conclusions are presented and discussed under three frameworks of analysis in Section 4. Finally, conclusions, recommendations and future research are presented in Section 5.

2. Basic concepts

2.1. Renewable energy supply chain (RESC)

As stated by the U.S. Energy Information Administration [32] renewable energy sources regenerate, unlike fossil fuels, which are finite. According to [32], there are five renewable energy sources in the world which are commonly used: biofuels which includes biomass (wood and waste), ethanol, and biodiesel; hydropower; geothermal; wind; and solar. Biomass is one of the most important renewable energy sources used in the United States. Fig. 1 shows the U.S energy consumption by energy source in 2016 [32].

On the other hand, the International Energy Agency [33] also includes among its renewable energy sources, five different technologies to extract energy from the oceans: Tidal power, Tidal (marine) currents, Wave power, Temperature gradients, and Salinity ingredients. However, few of these technologies have been deployed as yet and they must be further analysed and researched [33]. Currently, sustainable energy supply is based on four important basic technologies available in the market: biomass, hydropower, wind, and solar energy [32]. The energy demand should be balanced considering the different alternatives of energy available in the regions according to the production as well as the main problems, issues and trade-offs associated with different decisions in its management [32].

In order to reduce dependency on fossil fuels and move towards to energy efficiency, RE has been promoted as the alternative source of energy. Wee et al. [34] presented an assessment of RE sources from a supply chain perspective and an investigation of RE focusing on four main components: renewable energy supply chain, renewable energy performance, barriers and strategies to its development, considering biomass, hydropower, geothermal, wind and solar energy sources. Fig. 2 presents a RESC flow proposed by the United Nations Development Programme in 2010 [34,35]. The research topics in logistics and

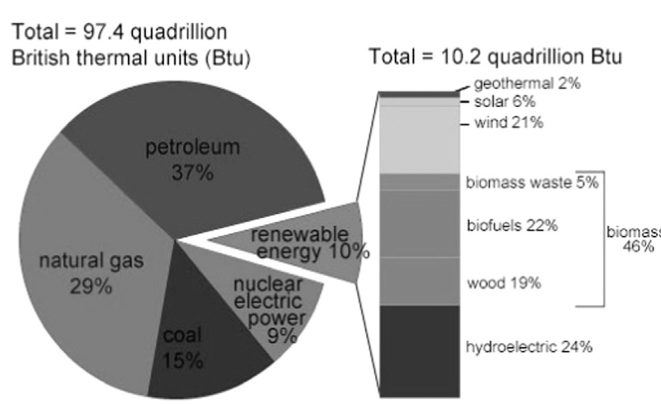

Fig. 1. U.S. energy consumption by energy source, 2016. Source: retrieved from [32].

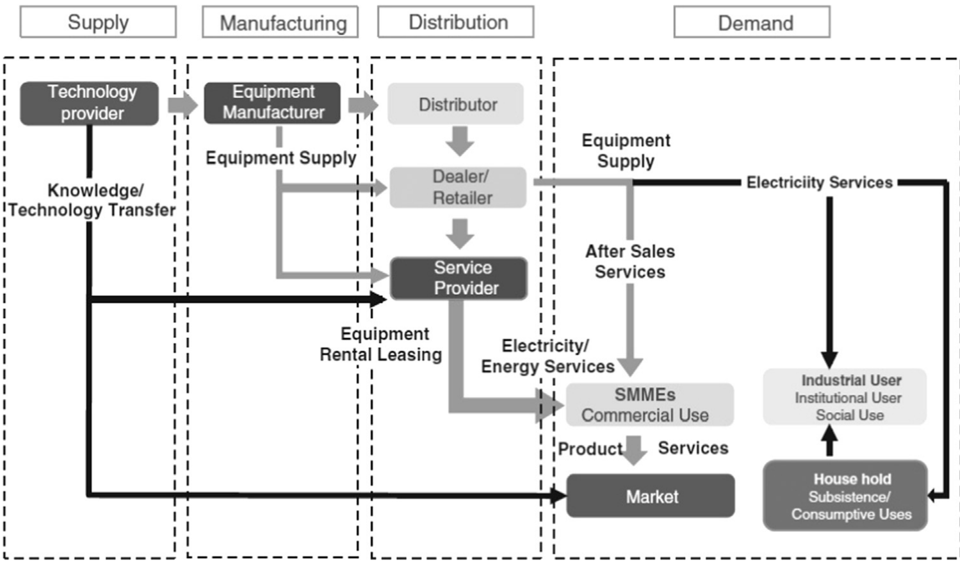

Fig. 2. Renewable energy supply chain. Source: retrieved from [35].

supply chain management have been traditionally associated with inventory management, forecasting, transportation and network optimisation. Energy supply has become one of the world's major issues and it has been analysed with the aim of applying traditional methods to energy supply networks, e.g. [36–38].

RE use and distribution are major tasks in RESC because of uncontrollable variables and renewable energy performance related to conversion efficiency, which includes storage, distribution, efficiency, and secondary application efficiencies [34]. As in many typical supply chains, elements of RESC include physical, information, and financial flows and each aids industries trying to increase awareness about green manufacturing processes, logistics and products in order to increase the SCM performance [34]. Moreover, technology is a key factor to improve efficiency and to innovate the distribution network, and the commercialization of RE creates a need to find new alternative sources unlike those of the traditional fossil energy [34]. Table 1 shows the main factors for each stage in RESC in the use of renewable energy resources based on [34].

In this analysis, three key variables of RE resources that require effective management and control were identified: intermittency (e.g. solar source), variability (e.g. biomass source), and manoeuvrability or flexibility (e.g. electricity power). These variables are presented in all processes of RESC and should be considered in depth. Sustainability plays a role in these types of energy, but Wee et al. [34] claim that the three dimensions (economic, environment and social) are barriers to RE development. In this work, we consider that sustainability is important to improve the supply chain management of renewable energy from a holistic perspective because of its dynamic aspects related to sustainable development, i.e. economic, social and environmental sustainability.

In order to understand the main features of biomass, wind and solar energy flows a brief description is presented below.

2.1.1. *Biomass energy flows*

According to the International Energy Agency [33], Biomass "*is any organic, i.e. decompostable, matter derived from plants or animals on a renewable basis.*" This includes agricultural, forestry, and industrial waste as well as manure. There are several technological processes available to convert this waste into usable energy resources and products, and the most common are ethanol and biodiesel. Fig. 3 provides an overview of the biomass energy flow based on [34].

Goldemberg and Teixeira Coelho [39] have introduced a new concept regarding biomass. They refer to "modern biomass" as a RE resource produced in a sustainable way, i.e. biomass used for electricity generation, heat production, and transportation fuels, made from agricultural and forest residues, as well as solid waste [39]. Biofuels remain one of the few options to replace the role of fossil fuels in the transport sector [40], and they are one of the most sustainable alternatives for the future.

2.1.2. *Wind energy generation flows*

This type of energy is not new and has been used to pump water in farms for many years. For centuries, windmills were used to grind grain, but the wind turbines that generate electricity today are new and innovative [32]. Fig. 4 provides an overview of the wind energy generation flow based on [34].

Currently, wind turbines are located both on-shore and offshore and the latter are used to collect massive wind power and to lower the environmental impact on land usage. However, offshore projects require complex logistics management due to the operations related to platforms, turbines, cables, substations, grids, among others, as well as transport [41]. On the other hand, some variables must be considered

Table 1
Factors of renewable energy.
Source: Adapted from [34]

Supply	→	Production	→	Distribution	→	Demand
• Land usage • Water consumption • *Intermittency* • *Variability* • *Manoeuvrability* • Technology limits		• Location • Conversion efficiency • High investment • Cost too high • Technology limits • O & M costs • Employment		• Distribution efficiency • Storage • Employment		• Environment impacts • Government policy • Substitution effect • Social impacts

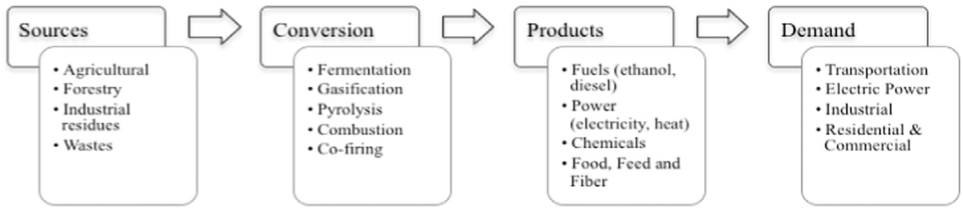

Fig. 3. Biomass energy flows. Source: adapted from [34].

in the analysis, such as the seasonality of the wind speed and direction [42]. In addition to the stochastic nature of the wind, forecasting of wind power generation plays an important role in any electricity system [43].

2.1.3. Solar energy generation flows

An important and widely used renewable energy type in the world is solar. It can be converted into electricity in two ways: Photovoltaic (PV devices or solar cells) and Solar thermal/electric power plants. Fig. 5 provides an overview of the solar energy generation flow based on [34]. Tropical countries are at a great advantage when it comes to this type of energy but energy storage is essential to supply fluctuating energy demands further taking into account variations in the intensity of sunlight [34].

In the renewable energy sector, e.g. bioenergy, geothermal, hydropower, ocean, solar, and wind subtopics, the application of system dynamics is scarce. Just a few papers use this approach to analyse transport and demand between distribution centres as well as the difficulty of investing in refining capacity and crops, e.g. [44].

Transport and demand are among the most common issues studied by researchers and practitioners; therefore, there is an opportunity to consider the global supply chain and its integration with the renewable energy supply chain processes from a dynamic perspective. The next section introduces an overview of the system dynamics approach and some applications in SSCM and RESC.

2.2. Overview of the system dynamics approach (SDA)

The system dynamics approach is a simulation technique created by Professor Jay W. Forrester in the 1950s to help managers improve industry processes whose behaviour is essentially dynamic. His work integrates concepts of feedback control theory and digital computation, explaining the behaviour of social systems and designing effective policies to improve system performance [45,46]. Forrester published extensively on SD and his main ideas were collected in three important books [47,48].

SD theory provides a set of tools and techniques to develop shared models of organisational systems, allowing rigorous representation, validation through simulation and evaluation of impacts of alternative policies by sensitivity and "what-if" analyses. This method and computer modelling techniques support managers by improving their understanding of the industrial processes whose behaviour is dynamic, or do not operate under steady state conditions [4].

The system dynamics modelling is based on three principles: *i)* the structure determines the behaviour e.g. a supply chain which involves complex interaction between components (customer, retailer, wholesaler, distributor, factory, and raw material supplier) in addition to order and material flows and decisions to be taken on these flows *ii)* the structure of organisational systems often involve "soft" variables – the structure of a supply chain must understand the perception of its agents regarding the future behaviour of consumers, and, *iii)* significant leverage can be obtained from the understanding of the mental model and changing it [4,45,49,50].

SD theory also has many types of applications in a variety of areas such as planning and policy design, economic behaviour, public management and policy, biological and medical modelling, energy and environment, theory development in natural and social sciences, dynamic decision making, software engineering and supply chain management [31]. Its use has been growing in the last five years, but it also needs to be studied more in supply chain analysis.

Sterman [4] defined the modelling process with system dynamics as an iterative and continuous process of hypothesis formulation, validation, and revision of the mental and formal models which represent the system. Based on this, materials, information and finance flows can be managed and coordinated using a system dynamics approach [4].

2.2.1. Sustainable supply chain management and system dynamics

Many reviews about SSCM have highlighted the advances in this field and the importance of truly sustainable supply chains [1,2,51]. Touboulic and Walker [52] comment that the theory-building efforts in SSCM remain scarce, as well as the possibility of new contributions in the development of new frameworks in this field. Some papers provide an analysis of research progress about SSCM [1,2,53].

Operations in the industrial sector engage activities that preserve the environment, communities and the development of projects allowing a long-term of economic feasibility [53]. Organisational sustainability on a broader level consists of three components: the natural environment, society, and economic performance perspective, which balance the economic, social and environmental issues from a microeconomic point of view [53].

On the one hand, no distinguishable sustainable approaches between industries, consumer products and transportation industry have been found. However, the possibility of going deeper into a particular industry, identifying specific types of sustainable activities and observing how the proposed theory on sustainable supply chain management may or may not be applied (e.g., renewable energy) remains open [53]. Therefore, examining a series of activities involving operations, logistics and design related to the integration between sustainability and the supply chain should be investigated [54]. On the other hand, brand value, the misuse of resources, government intervention and international regulations are critical elements in the implementation of sustainable practices [55].

Hassini et al. [6] proposed a conceptual framework highlighting the importance of reliable performance measures. This work is based on a

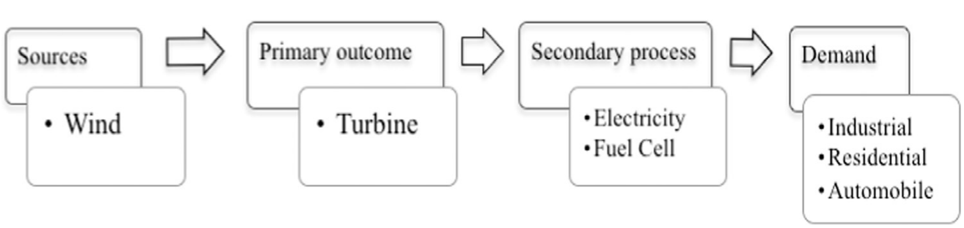

Fig. 4. Wind energy generation flows. Source: adapted from [34].

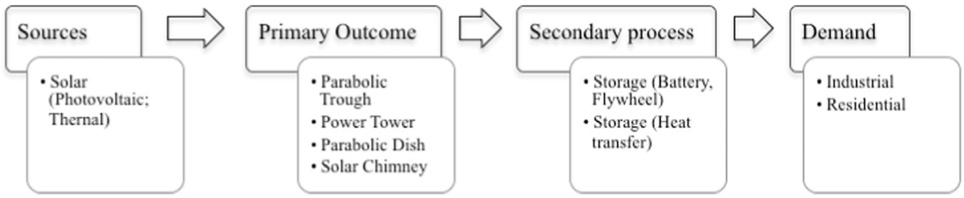

Fig. 5. Solar energy generation flows. Source: adapted from [34].

case study related to the energy sector and presents some sustainability indicators linked to its core management infrastructure and influenced by the relationships with stakeholders, i.e. customers and government. One case involving a system dynamics model was presented to predict the behaviour of alternative policies of long-term through "what if" analysis and using the total profit of supply chain as a metric of performance [56] in [6].

Seuring [5] identified the main modelling approaches and elements in SSCM. These comprise: Life Cycle Assessment–LCA (environmental impacts); Equilibrium models (balancing environmental and economic factors); Multi-criteria decision-making–MCDM (economic and environmental criteria optimisation); and Analytical Hierarchy Process–AHP (decision process structuration). On the other hand, Brandenburg [8] analysed approximately 134 works on decision making based on multi-criteria analysis. Twenty-eight works described holistic management models of sustainable supply chains, i.e. models that cover all sustainability dimensions, demonstrating that the integration of economic, environmental and social issues is one of the most recent areas of research to be developed [8].

Brandenburg and Rebs [9] provided some guidelines to construct a formal model. Due to the complexity of SSCM, some models still do not cover all sustainability dimensions nor win-win situations and the holistic dimension represented only 22% of the sustainable supply chain analysis. SSCM modelling is considered a young area and quantitative SSCM models have a clear focus on planning processes and manufacturing aspects, while retailers and wholesalers have been neglected so far [9]. On the other hand, the application of system dynamics was only reflected in one study where a macroeconomic perspective was used to assess economic and environmental impacts, i.e. pollution emission standards [9].

The application of SD modelling on Supply Chain Management (SCM) has its roots in Industrial Dynamics and the model structure has been described, analysed, and explained in terms of six interacting flow systems, namely the flows of information, materials, orders, money, manpower, and capital equipment [31]. Forrester's [45] model of a supply chain is one of the early examples. He considered the supply chain as part of an industrial system in terms of policy design, while other researchers have covered topics ranging from inventory management to global supply chains integration [31].

Building an adequate supply chain model requires three important elements, namely, people, observation and systems-knowledge, and system dynamics modelling proves to be a powerful tool for achieving enhanced performance in the chain [14]. Angerhofer and Angelides [57] presented an overview of SD Modelling in SCM classifying research work divided into three groups: (1) research concerned with theory-building; (2) research using SD modelling for problem-solving; and (3) research work on improving the modelling approach. The works focus on inventory decision and policy development, time compression, demand amplification, supply chain design and integration and international supply chain management [57].

All SD studies are considered empirical and the models are more descriptive than normative. SD focuses on feedback loops, accumulation processes and delays and it is considered as a powerful tool for analysing the dynamic tendency of complex systems [58]. A system dynamics approach aims to untangle the complex interrelationships between system components, processes, boundaries, objectives and stakeholders. The lack of studies applying SD in the last decade is an opportunity to develop the system dynamics field in SSCM applications.

2.2.2. Renewable energy supply chain and system dynamics

Some works on SCM demonstrate a particular interest in the performance of sustainability in supply chains; others in the analysis of greenhouse gas emissions. Wee et al. [34] provide managerial insights on different renewable energy forms focused on supply chain. The main difficulties in the generation and use of renewable energy are related to the conversion cost, location constraints and the complexity of distribution networks [34]. A review on the supply chain of renewable energy to improve its performance associated with control costs, demand management and flexibility can be found in [3]. Gold and Seuring [59] covered the interface of bioenergy production and issues of logistics and supply chain management to present a state of the art related to all three sustainability dimensions of bioenergy systems, i.e. economic, ecological and social/human aspects.

Although there is scarce literature about renewable energy supply chains, significant interest in renewable energy as a whole is emerging. In general, the demand for energy is shifting toward cleaner fuels such as natural gas, renewable sources and nuclear energy. Firstly, one-third of the world's energy will be provided by oil in 2040. Secondly, 40% of the growth in the global energy demand from 2014 to 2040 is expected to be supplied by natural gas. Modern renewable fuels – wind, solar, and biofuels – also will grow rapidly. Globally, these sources will more than triple from 2014 to 2040. The largest volume growth will come from wind energy, which by 2040 is expected to supply about 2% of the world's energy, and nearly 10% of its electricity [60].

In this scenario, SD modelling has been used for strategic energy planning and policy analysis for more than forty years. It began with two models developed at the MIT, called WORLD2 and WORLD3, in the early 1970s [4]. These models analysed the long-term socioeconomic interactions that caused and, at the same time, limited the exponential growth of the world's population and industrial output. Considering the limit of natural resources available on Earth, the exponential growth in their use would lead to their depletion and to the overshoot and collapse of the world socioeconomic system [4].

Naill and Belanger [61] developed a disaggregated model based on the life cycle theory of discovery and production of oil and gas. They concluded that the production of US domestic natural gas would continue to decline well below the rate of US natural gas discovery in the late twentieth or early twenty-first century. On the other hand, Sterman [4] proposed a system dynamics energy model that captured, for the first time, significant energy-economy interactions. Sterman highlighted that models proposed by Naill the energy sector is modelled in isolation from the rest of the economy [62].

SD is a powerful method to gain useful insight into situations of dynamic complexity and policy resistance. The energy sector is one of the most complex systems in the world considering the political, economic, environmental, and social factors as well as the synchronisation between production and use of energy in the most efficient way [63]. Economic activities and their dynamic behaviour affect the demand for production and prices as well as decrease or increase investment in the sector, which often causes changes in energy demand.

The application of the SD approach in the energy sector has increased since 1973 and it has been adopted in many decision-making procedures. The approach allows the analysis of the relations between different sectors of energy systems, such price fluctuations, increasing costs, growing demand, pollution and environmental concerns, political issues, among others [64].

Some applications have been found in particular sectors of renewable energy, such as bioenergy, including biofuels, and solar, e.g. [65]. This work presents simulation results related to the target reduction of CO_2 emissions and its impact on the investment attraction. From this perspective, the study of the renewable energy supply chain is an opportunity to apply the system dynamics approach and validate its potential in different kinds of energy sources [65].

For instance, the Biofuels Supply Chain (BSC) involves a large number of variables and delays, which interact over time causing loops and making the analysis extremely difficult without a model [66]. The main problem in the biofuels sector is the debate regarding its sustainability, and its environmental and economic feasibility. However, social issues have high impact on investment decisions in the sector considering, among others, land use for this purpose [66].

Franco et al. [44] present a model of learning designed to understand the effects of biofuel supply policies in the sugar cane and oil palm sectors. According to the model results, alternative or additional policies could be introduced to accelerate the growth in the production of biofuels in Colombia. The SD model helps in the understanding of biofuel supply and demand to analyse the behaviour of the supply chain and the response of this system to different policies [44]. Fig. 6 shows the Forrester Diagram of the investment in refining capacity.

Biorefinery systems can be considered complex systems. This is because they include operations such as biomass plantation, harvesting, supply, pre-treatment, conversion, separation, and finally bioenergy and bioproducts distribution [67]. The SD approach could support the integration of this whole chain providing benefits for the three dimensions of sustainability (economic, environmental and social).

3. Methodology

Different methods to identify potential research gaps and highlight the boundaries of knowledge have been the used in recent literature reviews [5,8,9,59,68]. Content analysis has been the most widely used method, e.g. [59]. A structured literature review however, consists of an iterative cycle of defining appropriate search keywords, searching the literature, and completing analysis [69]. This review aims to provide an overview of the application of SD in RESC focusing on the contribution to sustainable and renewable energy supply chain systems.

Thus, based on the above and from literature reviews published in peer-reviewed journals [16,59,70,71], a search strategy was performed using the following steps:

a) Defining the appropriate search terms: The keywords used for data collection were defined to capture articles relating to the area of renewable energy supply chain and applications of the system dynamics approach. Two keyword strings were developed. The first one included the most important renewable energy sources. The second was based on different literature reviews about the topic of system dynamics applied to the energy sector, i.e. [16,71–73]. The following keywords strings were used in the search field of Scopus: ((“renewable energy” OR wind OR solar OR biofuels OR bioenergy OR biomass) AND (“supply chain” OR logistics) AND (“system dynamics” OR “system* thinking” OR “system* model*” OR computer simulation)). Both aspects are covered by these keywords considering that this work focuses on the use of System Dynamics in Renewable Energy Supply Chain from a sustainable and systems perspective.
b) Collecting publications and delimitation: The unit analysis for this study was defined as a single research paper. The review took into account English-speaking peer-reviewed journals. A starting point was set at 2007 (last ten years) using the “title, abstract, keywords” search in Scopus database, and it was also bounded to only include scientific research papers: (1) stored in journals (conference papers, books and chapters of books were excluded) for the defined search terms, (2) focused on system dynamics approach, and (3) focused on the renewable energy area. The keywords search strings comprised the title, abstract and keywords in Scopus database. This search identified 88 papers of which only 10 were directly related to the scope of this review.
c) Material evaluation: The material was reviewed and analysed according to descriptive analysis, that is, publishing trends in the area, geographical position, author citations, and sources of renewable energy were considered in the analysis. However, a framework of analysis is presented according to the research objective, and therefore, all the scientific works were evaluated to identify the focus on the use of the SD approach in the supply chain as well as the importance of the three sustainability dimensions (economic, environmental and social) in each paper.

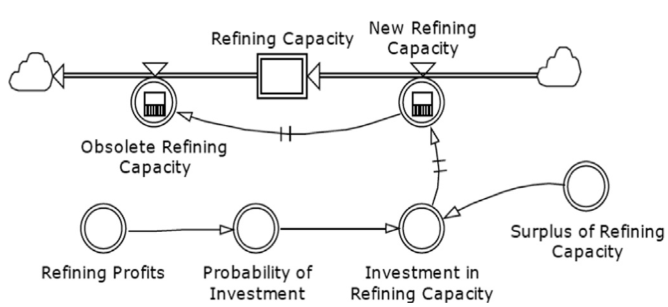

Fig. 6. Forrester diagram of investment in refining capacity. Source: retrieved from [44].

This review did not intend to cover the entire literature but rather provide an informative and focused evaluation of the selected literature in the application of system dynamics in RESC, which should support the research objective previously outlined. The following section provides the main findings and discussion of this literature review.

4. Findings and discussion

4.1. Initial search results and refinement

The first step comprised the evaluation of scientific works, published between 2007 and 2017 (until May). The initial search resulted in a total of 88 papers. After refinement, a total of 10 journal papers were selected. Fig. 7 shows the distribution of the papers selected over the time period.

The SD applications are related to the policies presented in markets, manufacturing and industrial sectors but not in supply chain analysis associated with the energy sector. In any complex dynamic system, feedback, time delays, stocks and flows (accumulations) and nonlinearity are important elements for understanding the system behaviour and improving decision making [74].

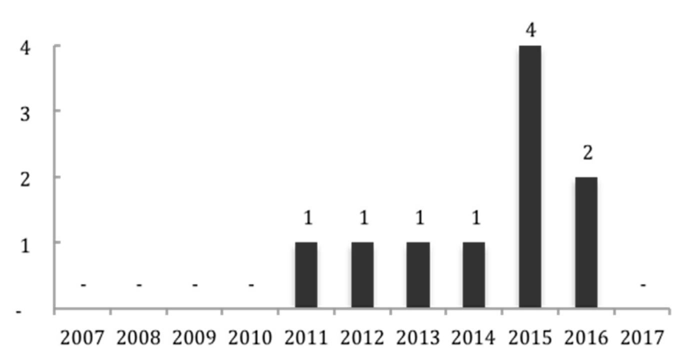

Fig. 7. Distribution of the papers selected between 2007 and 2017 (until May).

Table 2
Distribution of reviewed papers.

Journals	Author (year)	Regions	Technology	Global citation
Sustainability	Halog and Manik (2011)	United States	Biomass	81
Applied Energy	Rendon-Sagardi et al. (2014)	Mexico	Biomass	15
PLoS ONE	Vimmerstedt et al. (2012)	United States	Biomass	11
Environmental Research Letters	Clark et al. (2013)	United States	Biomass	5
Journal of Cleaner Production	Sanches-Pereira and Gómez (2015)	Sweden	Biomass	4
Renewable and Sustainable Energy Reviews	Franco et al. (2015)	Colombia	Biomass	3
Renewable Energy	Azadeh and Vafa (2016)	Iran	Biomass	3
Biofuels	Newes et al. (2015)	United States	Biomass	1
Biofuels, Bioproducts and Biorefining	Vimmerstedt et al. (2015)	United States	Biomass	1
Agronomy Research	Horschig et al. (2016)	Germany	Biomass	0

4.2. Descriptive analysis

According to results shown in the previous section, little attention has been devoted to the topic of system dynamics in recent years. However, due to growing interest in the holistic perspective of the renewable energy supply chain this has been changing in the last two years [3,34].

Table 2 shows the distribution of reviewed papers by journals, regions addressed, and "global citation" for each author. The importance of renewable energy issues in different countries around the world is especially related to the reduction of GHG emissions. Although there are a variety of references dealing with the SD approach and renewable energy, most work concentrates on biomass technology and its different uses such as ethanol, biodiesel and biomethane.

The lack of works related to the RESC as a whole suggests that many researchers have not regarded the SD approach as a tool. One reason could be that it is not considered as robust as mathematical models. However, SD has been extensively used as a decision support method in the energy sector, however, mainly focused on government agencies at the regional and national level and designing policies in the field of energy policy and electricity-related policy settings [16,71].

4.3. Framework of analysis

Some approaches in SCM have been analysed for sustainable products and others for sustainable operations [75]. The former takes the design of products into account, and the latter involves operational aspects, i.e. logistics, network design, waste management, transportation and distribution, as well as sustainable manufacturing [75]. With this approach, the integration between the operations across multiple stakeholders to reduce duplication and redundancy and the coordination the flow of materials, products and information between supply chain partners and the end consumer constitutes a challenge.

In a similar approach, a review of models using SD methodology in RESC is presented in this work. The categorical distribution of articles is determined by the use of the SD model and its application area. Therefore, three categories were identified: Biomass Scenario Model (BSM), Sensitivity Analysis and Hybrid Modelling. As will be summarized in Section 4.4, renewable energy and supply chain issues are modelled with SD at different stages of the supply chain with a long time horizon of 10 years and more.

4.3.1. Biomass Scenario Model (BSM)

One particular work involved the application of the system dynamics approach to evaluate the biomass-to-biofuels supply chain in the National Renewable Energy Laboratory-NREL (Biomass Scenario Model – BSM [72]). This model was designed for different purposes related to biofuel landscapes, potential areas, logistics, and supply chain for the biofuels industry in the U.S. The BSM of ethanol focused on distribution logistics, dispensing stations, fuel use and vehicle modules, and was designed to support biofuels policy by determining what supply chain changes had the greatest potential to accelerate the deployment of biofuels [23].

The BSM is based on the evolution of SC for biofuels and its inputs are related to the marketplace structure (producer and consumer exchanges, investment, financial decisions); government policies (analysis, implications, inclusion decisions/scope); and input scenarios (feedstock demand, oil prices, learning curves). A dynamic perspective focused on a year-to-year scale management [23]. Fig. 8 shows the full supply chain for ethanol fuel. This work focused on the last two phases: Biofuels Distribution and Biofuels End-Use, considering that the station owners represented a key variable in the analysis because they decided the biofuel supply according to market conditions (availability, infrastructure) and risks associated with the investment required [23].

A consumer's choice approach (based on national choice theory and model price), and the availability of retail biofuels as determinants of consumer's choice were considered [23]. Thus, three scenarios were established: "No policy" case without incentives, a "Higher market and infrastructure" case with higher levels of incentives, and a "Lower market and infrastructure" case with lower levels of incentives [23].

Market incentives (point-of-production subsidy; point-of-use subsidy; incremental gasoline cost), and infrastructure incentives (distribution and storage subsidy; repurposing subsidy; fixed capital investment subsidy) were the policies considered in the model. According to the simulation process, a high level of ethanol consumption is possible if there is a strong policy based on substantial subsidies and high levels of market penetration. On the other hand, this requires the availability of infrastructure and favourable market conditions across the entire supply chain [23].

One of the sectors that most contributes to the growth of the biofuels industry is the conversion sector. Therefore, Vimmerstedt et al. [12] analysed industrial expansion considering four operational scales (pilot, demonstration, pioneer-commercial, and commercial) in terms of five types of performance improvement (conversion-process yield, feedstock-input capacity, capital cost, investor risk premium, and access to debt finance). The information exchange between the BMS modules and their connections comprises a reinforcing feedback attracting investment in capacity expansion, i.e. a rapid industrial growth and maturation of the industry [12].

A literature review with emphasis on biomass-to-biofuels

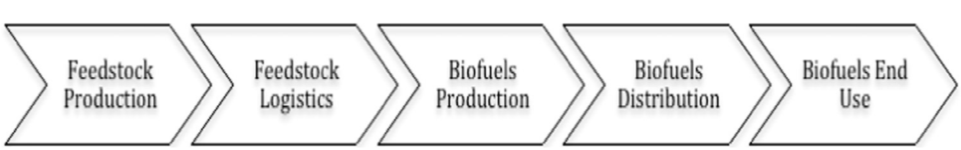

Fig. 8. Supply chain for ethanol fuel (Biomass-to-biorefinery).

Table 3
BSM studies.

Author (s) (year)	BSM Scope	Module Focus	Results
Vimmerstedt et al. (2012)	Exploring the biofuels distribution and biofuels end use of the supply chain	Downstream	High penetration of ethanol requires substantial subsidies (policies intervention)
Clark et al. (2013)	Examining the CRP in biofuels industry development (Land Use)	Feedstock Production	Large-scale conversion of CRP to row crops would incur a significant environmental cost but not benefit of biofuel production
Newes et al. (2015)	Exploring the policy environment surrounding cellulosic ethanol	Feedstock Supply; Conversion; Downstream	Focus on biorefinery development, initiatives, and dispensing stations are required to facilitate expansion
Vimmerstedt et al. (2015)	Exploring the rapid expansion of biofuels production	Feedstock Conversion	Rapid growth in volumes of sales implies coordinated investment, management of risk and uncertainty, and conversion sector barriers

conversion was carried out [12] in order to identify bioenergy modelling analytic needs and to highlight the application of BSM. Four bioenergy modelling analytical needs were identified: the need for holistic models, the need to understand the value of coordinated decisions, the need to support technology investment decisions, and the need to assess the impacts of incentives. These needs focused on the biomass supply chain design, analysis and modelling with special emphasis on optimisation models [12].

Moreover, a set of BSM scenarios was defined to examine the development of the biofuel industry. Incentive policies, facility expansion limits, ethanol use, and learning-by-doing assumptions were explored. The main conclusions show that incentives are a critical point in the expansion of the biofuels industry; capacity expansion requires more market pressure to consider greater infrastructure; policies on the ethanol use need to be changed for the biofuels industry; and technology needs to be developed in different pathways of maturity [12]. On the other hand, there are limitations in BSM related to the input data, model features and scenario design, which should be explored, analysed and evaluated if the biofuels industry is to grow rapidly.

In a similar work, Clark et al. [22] used BSM to analyse the complex technological, economic, and logistic development and dynamics of the entire biofuels industry. The authors analysed the role of the Conservation Reserve Program (CRP) in the development of the cellulosic biofuels industry. CRP allocates land for the expansion of the production of biofuels in the USA, as well as providing habitat for wildlife, it also evaluates the use of land for this type of crop [22].

The SD model examined seven land-use scenarios (some of CRP cultivation for biofuel) and five economic scenarios (subsidy schemes) to explore the benefits of using CRP. Some of the concerns include the impact of expansion and agricultural intensification and the lack of developed infrastructure that could affect the economic viability of the industry [22]. Six categories of concerns were considered associated with the environmental impact: water quality, water quantity, soil quality, air quality, terrestrial and aquatic biodiversity, and invasion of feedstock crops. The five subsidy scenarios were: minimal policy; only ethanol; Renewable Fuel Standard; out-put focused; and diverse pathways [22].

Five feedstocks were used: corn and soy (considered first-generation feedstock), and corn stover, perennial grasses, and woody biomass (considered second-generation feedstock) [22]. Based on the simulation model, large-scale conversion of CRP to row crops would incur a significant environmental cost, without a large benefit in terms of biofuel production. In terms of environmental impacts, with first-generation feedstocks there was a greater risk for negative effects, while second-generation feedstocks there was greater potential for positive environmental effects [22]. The final conclusion of the use of BSM is that it seems a useful tool to demonstrate the magnitude of the policies for conservation of marginal lands as well as the use of economic policies, showing how the system behaves [22].

Some initiatives have been important in reducing dependence on fossil fuels as well as GHG emissions. Whether economic or financial incentives, the development of the ethanol or biodiesel industry requires an analysis between incentives and production across the supply chain [21]. BSM was used to explore a full-supply-chain understanding of the points of leverage that could sustain biofuels industry and to provide theoretical insight to support its growth [21].

Gasoline pricing, industry learning, and financing in the development of the ethanol industry have been the main analyses performed using BSM [21]. These analyses were established in three sectors, i.e. feedstock supply and logistics, feedstock conversion and downstream [21]. An analysis with and without a range of incentives was performed using BSM, which showed that external assistance to the development of the cellulosic ethanol industry is required. In addition, government policies and potential system synergies will facilitate investment initiatives, industrial learning, and a self-sustaining industry [21].

The Biomass Scenario Model has been developed to investigate the dynamics associated with biofuel industry in the United States, to generate scenarios for the evolution of biofuel transportation fuel industry, and for analysing and evaluating impacts and discussion among policy-makers, analysts, and stakeholders [12,21–23]. Table 3 shows the studies simulated by BSM and its main characteristics in the present study. Although the Department of Energy (DOE) and other government agencies have used this model, the biofuels industry in the private sector still does not use it at all.

4.3.2. Sensitivity analysis

Scenario analysis is frequently used to analyse different future events. This process is often used in applications of system dynamics to analyse for example, the main variables and feasibility of biofuel supply chains in different regions. A SD application was used to analyse five possible scenarios and evaluate the availability of area for the sowing of sorghum and sugarcane crops [24]. The model produced significant information about future conditions of Mexican biofuel production and supply. SD has been used as a powerful tool to understand biofuel supply chains in emerging markets such as Mexico [24].

The SD modelling considered the following conditions: continuous production and trends for demands of different sectors for agricultural industry, and on the other hand, the production capacity of ethanol and gasoline and trends for fuel demand for the energy industry [24]. Likewise, based on previous studies [4,77], four stages were developed for the SD model: conceptualization, formulation, evaluation, and implementation. The formulation stage included techniques such as a case study, forecasting and the system modelling. In the evaluation stage, verification and validation of the simulation model were performed. Finally, in the implementation stage the results were analysed to support the decision-making process [24].

According to simulation process and the sensitivity analysis of five different scenarios (five different percentages related to production, supply, and demand of biofuel and gasoline), the model concluded that only 0.8% of the total fuel domestic demand would be the result of blending ethanol with gasoline between 2014 and 2030. On the other hand, the amount of CO_2 would be reduced by 1282.95 million tonnes in the same period [24]. These results show that SD model is a valuable tool to analyse both feasibility and environmental conditions in the use of renewable energies.

Many researches and practitioners have tried to monitor the development of different systems in order to evaluate their behaviour using an analytical framework. For instance, system dynamics has been used to evaluate the impact of the Swedish biofuel system on the use of 10% renewable fuels by 2020 and to identify some patterns in order to establish a vehicle fleet independent of fossil fuels by 2030 [26].

The Swedish vehicle fleet consists of approximately 62.78% personal cars, 7.86% heavy-duty vehicles or trucks, 0.20% buses, and 29.19% motorcycles [26]. Private cars, heavy-duty vehicles, and buses are fuelled by gasoline, diesel, bioethanol, and gas fuels, and represent approximately 71% of all vehicles used in Sweden. Biodiesel accounts for approximately 44% of the renewable energy mix used in domestic transport [26].

Three components (biofuel imports, local raw material, and raw material imports) were identified as drivers of the system´s oscillation or balance between external and internal growth patterns in the biodiesel supply chain. These variables were put under demand pressure in varying time frames: short-term – 2014, medium-term – 2020, and long-term – 2030. The results confirmed that biofuel imports is the variable that could guarantee the establishment of a vehicle fleet independent of fossil fuels by 2030. Due to its relationship with competition and pricing, it might require a strong policy framework to use biofuels in the transport sector [26].

However, factors such as investment uncertainty could be affecting the biofuel system. This is because bioenergy systems are still seen as risky by some investors, which implies that this trend affects long-term investment in bioenergy infrastructure, i.e. biorefineries or other biofuel production plants [26]. Furthermore, it is important to highlight that consistent and clear sustainability criteria related to land use changes are factors that have not yet been established for biofuel systems [26].

Biofuels have been considered part of the solution in the reduction of CO_2 emissions because of its use in the transport sector. In order to analyse the penetration of biofuels in countries where this type of energy is not regulated at all, a system dynamics model was used and evaluated in different scenarios [25]. The use of ethanol and biodiesel in conventional vehicles has been increasing in the last five years, and as a result governments have had to create new regulations for biofuel use which enables competition with fossil fuels. However, some countries require immediate action to reach the levels of countries such as Brazil and the United States, which are currently leaders in the production of ethanol and biodiesel in the world [25].

Franco et al. [25] identified that the use of system dynamics to investigate the bioenergy industry has been based on analysing for example the impact of biodiesel production, incentives for the biofuels market, and R & D investment, but not on the effect of the liberalization of biofuels in a particular country. Therefore four scenarios to analyse the biofuels market in Colombia using a system dynamics model were developed. These scenarios were assessed in a base-case scenario (with and without external market) and in a liberalized market (with and without external market). The SD model incorporated four key variables (investment in crops, refinery capacity, stocks of biofuels and fuel demand) [25].

According to the simulation results, important potential was identified related to land available, biofuels expansion, and a need for increasing R & D applied to the biofuels industry. However, present conditions limit the business activity of investors, as regulation does not stimulate this kind of investment. The potential of the system dynamics approach to understand possible system behaviours is given by the simulation of multiple scenarios under some assumptions based on similar cases. This allows the identification of key factors in the industry, e.g. biofuels, which can be described and considered for future research [25].

Another use of SD has been to determine future market shares for biomethane and bio-SNG (biologically produced synthetic/substitute natural gas) for Germany under varying scenarios such as incentive schemes, economy of scale and feedstock prices [27]. The importance of this type of energy for Germany has made it worth analysing the market structure to derive scenario-driven forecasts on future market shares for biomethane [27]. For the analysis, a techno-economic analysis and the Delphi-Survey were used to validate and calibrate the model based on three different scenarios: base (production and use of biogenic gas in the power, heat and transport sector); green heat (additional payment for green heat produced in environmental beneficial combined heat and power plants); and green transport (defined by a substitution of natural gas transport through biomethane) [27].

The results from applying the SD model showed that the base scenario would be reliable until 2030. The green heat scenario showed that with the current price for biomethane the additional payment for green heat should be reasonable to encourage further capacity installation. Finally, the green transport scenario showed that with the current price for biomethane, the additional support must be 50% less than in the green heat scenario. Therefore, and according to the above, for decision support it is necessary to formulate policy proposals to develop the potential market of bio-SNG in Germany until 2030 [27].

4.3.3. Hybrid modelling

The need to integrate methodological approaches for assessing systems has been widely discussed due to the increased complexity of problems. An integrative and holistic framework for sustainability assessment was developed in order to support policy formulation [10]. This framework adopted life cycle thinking methods – Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Social Life Cycle Assessment (SLCA); Multi-Criteria Decision Analysis (MCDA) and dynamic system modelling. In addition, System Dynamics (SD); Agent-Based Modelling (ABM); Data Envelopment Analysis (DEA) and Sustainability Network Theory (SNT) were used in the development of biofuel supply chain networks [10].

Considering that sustainability development is a complex and multidimensional phenomenon that cannot be completely managed by current tools, a new modelling framework has been developed to understand the challenges of sustainable development [10]. The framework considers the triple pillars of sustainable development. LCA is considered for environmental impact; LCC is applied for assessing all the costs associated with the life cycle of a product and SLCA describes the impact of an organization, product or system on society. MCDA is used for Stakeholder analysis, however; DEA is used to calculate eco-efficiency indicators or any other ratios (e.g. resource productivity); ABM is applied to consider the global consequences of individual or local interactions in a given geographical area; and SNT is used to model the understanding and visualization of the sustainable supply chain of biofuel systems by considering it a network [10].

The role of SD in the modelling framework is more representative. A preliminary Causal Loop Diagram is used to analyse the difficulties associated with the biofuels supply chain based on MCDA. Likewise, SD helps to understand the interrelationships among different components of the supply chain providing insights on systems synergy [10]. ABM (inductive-approach) and SD (deductive-approach) are the most appropriate approaches to explore the various “what if” scenarios considering the three main goals of a particular system. The author recommends the support of cyberinfrastructure to integrate the different software packages used in the system modelling framework [10].

A hybrid approach was used in this study to design and plan a biodiesel supply chain from the biomass fields to the consumer market with the premise that the supply chain faces limitations related to biodiesel production such as water resources and competition from fossil fuels [28]. Figs. 9 and 10 show the main outputs used by both the system dynamics model and the mathematical model.

Considering the biomass supply chain in Fig. 8, a system dynamics and a mathematical programming approach were used to model the whole system. The former was used to estimate the parameters used in a biodiesel supply chain in a given planning horizon, while the latter used these parameters as inputs in a stochastic mixed-integer programming

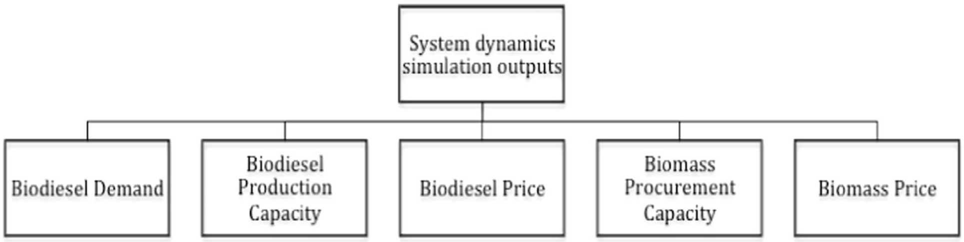

Fig. 9. System dynamics simulation outputs. Source: adapted from [28].

model to calculate the variables of the supply chain management problem and to achieve the maximum total profit for the biodiesel supply chain [28].

The framework used for SD and the mathematical model is able to provide a macro and micro view of the biofuel supply chain. However, all the decisions were based on the profit optimisation. Works based on the market share of biomass, technological development evaluation and production cost and development and performance of the SC have used mathematical models for this purpose [28]. On the other hand, SD has been considered strategic in this kind of problem in which the government changes the fuel market equilibrium through incentive policies for biomass and biodiesel producers [28].

4.4. Summary and proposed framework for SD modelling

In recent years the challenges associated with RESC has been centred on proposing policies related to climate change and GHG emissions with the objective of replacing fossil fuels. This study provides insights for current and future research directions in the field of RESC identifying the main characteristics of the supply chain and its modelling approach focused on system dynamics. Furthermore, special attention has been given to sustainable development, which plays an important role in the integration of the supply chain and renewable energy sources. Table 4 provides a summary of the review process.

Some literature reviews focused on identifying the key issues in the supply chain of renewable energy, e.g. design and performance and/or transport logistics [3,59]. The importance of overcoming the main barriers to the development of RESC is key to the supply chain performance by using analytical tools. Therefore, it is necessary to develop a framework that can identify all the variables involved within and among systems (e.g. biofuels supply chain system).

Some factors related to land use and investment are of great importance in the development of renewable energy systems [24,28]. However, the most critical factor is linked to an efficient supply chain and relationships with all stakeholders [26]. Sustainability criteria have not yet been widely addressed and therefore they deserve more attention and research in the area of renewable energy. This is the reason why some researchers consider sustainability in the whole SC from an environmental point of view, based on environmental indicators (e.g. CO_2 reductions and GHG emissions assessment) that must be measured and related to GSCM in a strategic planning approach [10,22,25,26].

A SD modelling approach attempts to map the structure, evaluating the decision impacts throughout simulation, and can contribute to the elaboration of policies and solutions to operate the system. Despite the fact that the Biomass Scenario Model (BSM) uses SD to model the supply chain, its application has been limited to a fraction of SC (e.g. downstream). Although results have demonstrated that it is useful in the environmental and economic dimensions of sustainability, the social aspect requires further research [12,22,23].

In order to evaluate the impact of determined markets, SD has been used in different countries. Based on a demand pressure scenario, biofuel imports represented a critical variable for the Swedish Biofuel System so as to ensure a fleet of vehicles using 100% renewable energy resources. However, a clear analysis of sustainability and land use are the main challenges that hamper progress in this sector [26]. In a similar model, a forecast scenario was used to determine the future for biomethane and bio-SNG in Germany. In this case, feedstock prices played an important role for production and use of this type of energy and SD provided support to decision making [27].

In this overview an opportunity to propose a simulation and a modelling-based framework as a method for implementing the SD approach was found. This framework is designed to analyse the dynamics of a supply chain in order to better support the implementation of SD models. As shown in Fig. 11, these four phases require an in-depth analysis by the integration of several phases related to the logistics of biofuels to improve the implementation of the SD model. Although this framework is a proposal for implementing modelling-based systems focused on SD, a brief description of each phase is included below but its development is not part of this work.

The first phase, *system characterization*, identifies and classifies the systems of the supply chain from the definition of the logistics cycle. The activities and processes carried out in each system and the resources associated with them are identified. This phase comprises the system, dependencies between activities, and identification and classification of resources and variables. The second phase, *structure analysis*, should be performed using a systems thinking (ST) approach whose main goal is to understand how the system works and its behaviour [4]. This phase identifies the key elements of the system and relevant strategies to improve the behaviour of the sub-systems. Therefore, relationships between variables and loops construction are analysed.

The third phase, *modelling*, integrates ST/SD, logistics cycle and renewable energy supply chains concepts using a causal loop diagram – CLD to identify the main features caused by an inadequate allocation. The most important issue in this phase is to determine if the model represents the real system through a continuous review of both the first and second phases. Finally, *validation and policies review*, applies a dynamic and integral method in terms of renewable energy supply chain concepts to establish priorities in the implementation of policies based

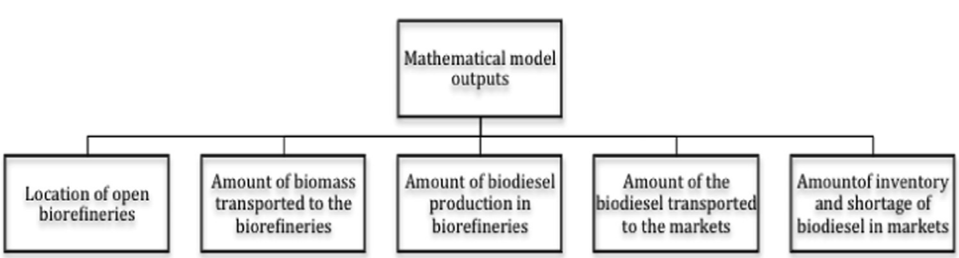

Fig. 10. Mathematical model outputs. Source: adapted from [28].

Table 4
Summary of the review process.

Author (s) (year)	General purpose	Model focus	Sustainability dimension
Vimmerstedt et al. (2012)	Evaluating biofuels distribution logistics	Incentives	Environmental-Economical
Vimmerstedt et al. (2015)	Evaluating biofuels conversion sector	Incentives	Environmental-Economical
Clark et al. (2013)	Evaluating economic and environmental scenarios for biofuels land-use	Land use	Economical-Environmental
Newes et al. (2015)	Introducing points of leverage for stimulating biofuels industry	Incentives	Economical
Rendon-Sagardi et al. (2014)	Developing an effective ethanol supply chain	Feasibility	Economical-Environmental
Sanches-Pereira and Gómez (2015)	Evaluating development biofuels impacts in transportation systems	Demand	Economical
Franco et al. (2015)	Liberalization of biofuels market in Colombia	Demand	Economical
Horschig et al. (2016)	Determining future market shares for biomethane	Capacity	Economical
Halog and Manik (2011)	Life Cycle Sustainability Assessment	Sustainability	TBL
Azadeh and Vafa Arani (2016)	Designing and planning a biodiesel supply chain system	Capacity	Environmental-Economical

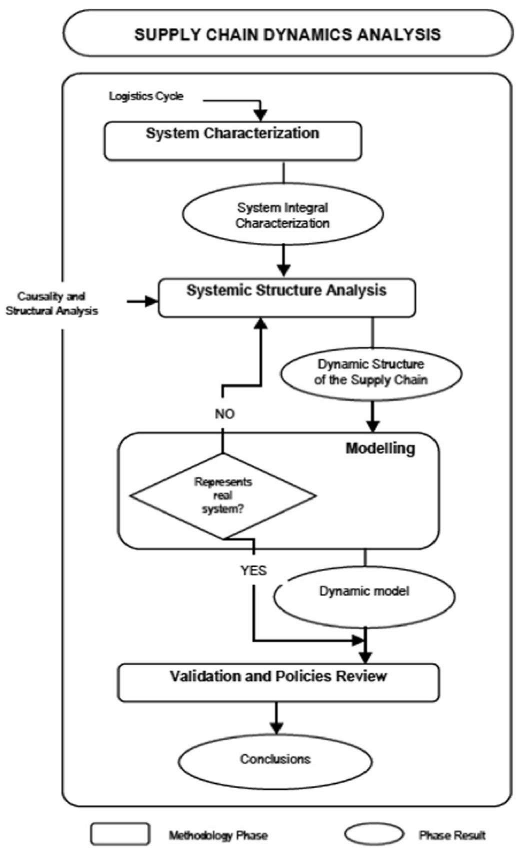

Fig. 11. A conceptual framework proposed for implementing a SD approach.

on the analysis obtained from the outputs of the modelling phase. Based on CLD, this phase enables the analysis of different policies related to supply chain performance, e.g. production processes, sustainability and stability.

5. Conclusions and recommendations

This overview presents and discusses some relevant issues about the supply chain in renewable energies and identifies some practices of the application of system dynamics approach for this kind of energy. The renewable energy most commonly used for the application of the SD tool has been bioenergy (i.e. biofuels: biodiesel, biomethane, ethanol). On the other hand, in the analysis of the supply chain, some papers have focused on the whole supply chain, while others on a part of the bioenergy supply chain (distribution logistics). They have used scenario analysis to evaluate the impact of the supply chain, as well as its behaviour in the whole system.

Some literature reviews focused on modelling techniques in sustainable supply chain management have shown how to reduce process costs by using operation research methods [5,8,9]. On the other hand, the method most used in Renewable Energy (RE) analysis is Life-Cycle Assessment (LCA) [3]. Few reports have shown the potential of applying a System Dynamics (SD) approach in the Renewable Energy Supply Chain (RESC). Therefore, the novelty of this paper compared to the related published literature lies in the use of the SD approach applied to RESC as a main topic. The aim of this study is to identify its main contributions, assumptions, limitations and opportunities for current and future works using a simulation-modelling-based framework as a system dynamics approach.

Although LCA is one of the tools used in RESC analysis, the possibility of using a dynamic perspective for determining the goodness of an energy system could be critical in decision-making. The importance of exploring and analysing the behaviour of the system modelled enables the researcher to focus on critical aspects of the supply chain (e.g. intermittency, variability, manoeuvrability) and not on policies that could be affecting its performance such as the total amount of CO_2 or other greenhouse gases emitted during the life cycle of a process.

The main finding in this study is that the use of system dynamics in the supply chain of renewable energy requires more research. Three bodies of work were identified in the literature review. First, the Biomass Scenario Model (BSM) was created to evaluate biomass-to-biofuels supply chain, but due to its complexity for Small and Medium Enterprises (SME's) it requires a greater comprehension and understanding in the use of each module. Second, the Scenario Analysis Process uses system dynamics as its main tool. However, it is not considered a forecasting tool and therefore requires another tool to complement the simulation methods. Third, a Hybrid Modelling Framework integrates different methodological tools to assess a complex system problem and the use of these multiple tools to assess the whole system represents a challenge for the SME's and practitioners.

In general, several works concluded that good infrastructure, favourable market conditions and strong relationships between stakeholders (not only the bioenergy market but also renewable energy in general) should be more sustainable. This means competitive prices, robust investment and enough knowledge about the advantages of the use of renewable energies instead of fossil fuels. These factors can be considered in another type of RE (e.g. offshore wind energy), as it is clear that the literature on wind and/or solar energy is scarce and their supply chains have been not analysed as a whole from a dynamic perspective.

Modelling of renewable energies from a macro view has not been investigated thoroughly in previous studies. This macro view should consider economic, social and environmental aspects of energy resources and therefore the system dynamics will consider complex relationships, feedback loops and delays, which can be modelled for renewable energy supply chain. It is also clear that the social aspect of the supply chain is absent from the sustainability concept and requires more attention within the supply chain of the renewable energy because of its importance in sustainable development.

According to the results and the main findings in the literature review, the main outputs can be summarized in three aspects, namely:

1) The Biomass Scenario Model (BSM) [76], proposed and supported by the National Renewable Energy Laboratory (NREL, U.S.), has gaps related to its use. The U.S. Department of Energy (DOE) and other government agencies have been its main users but the private sector has not yet applied it. Its potential covers a wide range of analysis areas within the biofuels industry such as biomass yield, climate change, trade and energy security [12,21–23]. This model has focused mainly on ethanol to accelerate biofuel deployment. By using a system dynamics model, BSM has demonstrated the need for substantial policy intervention, the importance of coordinating investment, land use and incentives with respect to timing, pathway, and target sector in the evolution of the biomass-to-biofuels market focused on cellulosic ethanol or lignocellulosic feedstocks [12,21–23].
2) 'What if' analysis is part of the simulation model. This enables the testing of different situations related to the system behaviour, which allows the analysis of certain policies using prototype models and the understanding of the dynamics of evolution of an emerging system based on scenario analysis [10]. Some assumptions related to the system behaviour are formulated considering a specific scenario (*base scenario*) which can be compared to other scenarios for the definition of strategies [25,27]. The potential of scenario analysis allows sensitivity analysis, evaluating the impact caused by the introduction of a new process or product into the system.
3) There is a need to integrate different tools in the analysis of complex systems in order to understand the whole behaviour through a hybrid framework [10,28]. This is useful if the problem requires different approaches and a micro and macro analysis considering the features of the parameters and the system behaviour [28]. Hybrid models could overcome the fact that Bottom-up and Top-down modelling on their own have weaknesses and limitations (e.g. lack of macro effects of the presumed technological change on overall economic activity or microeconomic realism), as an alternative for energy systems modelling [10]. There is an advantage if two tools are combined, however, if three or more tools are used, it is important to consider a good cyber-infrastructure to integrate computationally different software packages and modelling approaches to implement this framework [10].

Some authors recommend more frequent use of modelling and simulation as a way to explore a large number of scenarios in a specific context [12]. Many tools have the potential to analyse trends, assumptions, limitations and decisions about the system behaviour by providing important insights, however, it is important to take into account that the application of multiple tools requires more resources to analyse a variety of scenarios from different perspectives. Therefore, we consider that the proposed framework is a powerful and useful tool to identify research gaps and support the implementation of SD in the supply chain of renewable energy. For instance, in biodiesel supply chain management, the feasibility of importing biomass or biodiesel from developed countries and market conditions could be investigated [28].

This paper presents a comprehensive bibliography for future research in the bioenergy industry. On the one hand, several unresolved environmental and economic issues require an in-depth analysis across the supply chain, e.g., the lack of economic intervention and technological breakthroughs could be affect the growth on the biofuels industry [22]. On the other hand, current conditions in some developing countries differ in the use of biofuels, and new investment projects could be limited [24,25]. Therefore, simulations could help in assessing the different alternatives about the potential of the industry growth under environmental, economic and social conditions, as well as the feasibility of introducing new sources of second and third generation biofuels.

The use of SD continues to be an initiative in the analysis of the different barriers to renewable energy development by improving the renewable energy supply chain, which could be focus on conversion costs, location selection, and/or distribution networks. In order to improve supply chain performance, the main processes such as capacity, variability and flows could be included in a single model for analysis. Moreover, the social aspect should be included in the supply chain analysis if sustainability is a target for sustainable development.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors would like to thank the Federal Agency for Support and Evaluation of Higher Education (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES-BRAZIL) for its support through a scholarship to R.Saavedra. We would also like to thank the anonymous reviewers who provided helpful comments and suggestions to improve the quality of the paper.

References

[1] Seuring S, Müller M. From a literature review to a conceptual framework for sustainable supply chain management. J Clean Prod 2008;16:1699–710. http://dx.doi.org/10.1016/j.jclepro.2008.04.020.
[2] Carter CR, Easton L. Sustainable supply chain management: evolution and future directions. Int J Phys Distrib Logist Manag 2011;41:46–62. http://dx.doi.org/10.1108/09600031111101420.
[3] Cucchiella F, D'Adamo I. Issue on supply chain of renewable energy. Energy Convers Manag 2013;76:774–80. http://dx.doi.org/10.1016/j.enconman.2013.07.081.
[4] Sterman JD. Business dynamics: systems thinking and modeling for a complex world. Boston 2000.
[5] Seuring S. A review of modeling approaches for sustainable supply chain management. Decis Support Syst 2013;54:1513–20. http://dx.doi.org/10.1016/j.dss.2012.05.053.
[6] Hassini E, Surti C, Searcy C. A literature review and a case study of sustainable supply chains with a focus on metrics. Int J Prod Econ 2012;140:69–82. http://dx.doi.org/10.1016/j.ijpe.2012.01.042.
[7] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4:157–75. http://dx.doi.org/10.1016/S1364-0321(99)00011-8.
[8] Brandenburg M, Govindan K, Sarkis J, Seuring S. Quantitative models for sustainable supply chain management: developments and directions. Eur J Oper Res 2014;233:299–312. http://dx.doi.org/10.1016/j.ejor.2013.09.032.
[9] Brandenburg M, Rebs T. Sustainable supply chain management: a modeling perspective. Ann Oper Res 2015:213–52. http://dx.doi.org/10.1007/s10479-015-1853-1.
[10] Halog A, Manik Y. Advancing integrated systems modelling framework for life cycle sustainability assessment. Sustainability 2011;3:469–99. http://dx.doi.org/10.3390/su3020469.
[11] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 2014;29:394–416. http://dx.doi.org/10.1016/j.rser.2013.08.037.
[12] Vimmerstedt LJ, Bush BW, Hsu DD, Inman D, Peterson SO. Maturation of biomass-to-biofuels conversion technology pathways for rapid expansion of biofuels production: a system dynamics perspective. Biofuels Bioprod Bioref 2015;9:158–76. http://dx.doi.org/10.1002/bbb.1515.
[13] Moon YB. Simulation modelling for sustainability: a review of the literature. Int J Sustain Eng 2017;10:2–19. http://dx.doi.org/10.1080/19397038.2016.1220990.
[14] Towill DR. Industrial dynamics modelling of supply chains. Int J Phys Distrib Logist Manag 1996;26:23–42. http://dx.doi.org/10.1108/09600039610113182.
[15] Demczuk A, Padula AD. Using system dynamics modeling to evaluate the feasibility of ethanol supply chain in Brazil: the role of sugarcane yield, gasoline prices and sales tax rates. Biomass- Bioenergy 2017;97:186–211. http://dx.doi.org/10.1016/j.biombioe.2016.12.021.
[16] Leopold A. Energy related system dynamic models: a literature review. Cent Eur J Oper Res 2016;24:231–61. http://dx.doi.org/10.1007/s10100-015-0417-4.
[17] Sterman J, Oliva R, Linderman K, Bendoly E. System dynamics perspectives and modeling opportunities for research in operations management. J Oper Manag 2015;39–40:1–5. http://dx.doi.org/10.1016/j.jom.2015.07.001.
[18] Awudu I, Zhang J. Uncertainties and sustainability concepts in biofuel supply chain management: a review. Renew Sustain Energy Rev 2012;16:1359–68. http://dx.doi.org/10.1016/j.rser.2011.10.016.
[19] Sharma B, Ingalls RG, Jones CL, Khanchi A. Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renew Sustain Energy Rev 2013;24:608–27. http://dx.doi.org/10.1016/j.rser.2013.03.049.

[20] Nabavi E, Daniell KA, Najafi H. Boundary matters: the potential of system dynamics to support sustainability? J Clean Prod 2017;140:312–23. http://dx.doi.org/10.1016/j.jclepro.2016.03.032.

[21] Newes EK, Bush BW, Peck CT, Peterson SO. Potential leverage points for development of the cellulosic ethanol industry supply chain. Biofuels 2015;6:21–9. http://dx.doi.org/10.1080/17597269.2015.1039452.

[22] Clark CM, Lin Y, Bierwagen BG, Eaton LM, Langholtz MH, Morefield PE, et al. Growing a sustainable biofuels industry: economics, environmental considerations, and the role of the conservation reserve program. Environ Res Lett 2013;8:25016. http://dx.doi.org/10.1088/1748-9326/8/2/025016.

[23] Vimmerstedt LJ, Bush B, Peterson S. Ethanol distribution, dispensing, and use: analysis of a portion of the biomass-to-biofuels supply chain using system dynamics. PLoS One 2012:7. http://dx.doi.org/10.1371/journal.pone.0035082.

[24] Rendon-Sagardi MA, Sanchez-Ramirez C, Cortes-Robles G, Alor-Hernandez G, Cedillo-Campos MG. Dynamic analysis of feasibility in ethanol supply chain for biofuel production in Mexico. Appl Energy 2014;123:358–67. http://dx.doi.org/10.1016/j.apenergy.2014.01.023.

[25] Franco CJ, Zapata S, Dyner I. Simulation for assessing the liberalization of biofuels. Renew Sustain Energy Rev 2015;41:298–307. http://dx.doi.org/10.1016/j.rser.2014.08.025.

[26] Sanches-Pereira A, Gómez MF. The dynamics of the Swedish biofuel system toward a vehicle fleet independent of fossil fuels. J Clean Prod 2015;96:452–66. http://dx.doi.org/10.1016/j.jclepro.2014.03.019.

[27] Horschig T, Billig E, Thrän D, Thrän D. Model-based estimation of market potential for bio-SNG in the German biomethane market until 2030 within a system dynamics approach. Agron Res 2016;14:754–67.

[28] Azadeh A, Vafa Arani H. Biodiesel supply chain optimization via a hybrid system dynamics-mathematical programming approach. Renew Energy 2016;93:383–403. http://dx.doi.org/10.1016/j.renene.2016.02.070.

[29] Oliveira JB, Lima RS, Montevechi JAB. Perspectives and relationships in supply chain simulation: a systematic literature review. Simul Model Pract Theory 2016;62:166–91. http://dx.doi.org/10.1016/j.simpat.2016.02.001.

[30] Ba BH, Prins C, Prodhon C. Models for optimization and performance evaluation of biomass supply chains: an operations research perspective. Renew Energy 2016;87:977–89. http://dx.doi.org/10.1016/j.renene.2015.07.045.

[31] Singh S, Sharma PC, Pinto Barcellos PF, Rodrigues M. System dynamics as a tool for green supply chain management: a theoretical ransom. Int J Humanit Sci 2015;5:121–33.

[32] EIA – u.s. Energy Information Administration. Renewable energy explained; 2017 ⟨https://www.eia.gov/energyexplained/index.cfm?Page=renewable_home⟩ [Accessed 27 June 2017].

[33] IEA – International Energy Agency. Topics: renewables; 2017. ⟨http://www.iea.org/topics/renewables/⟩ [Accessed 27 June 2017].

[34] Wee H-M, Yang W-H, Chou C-W, Padilan MV. Renewable energy supply chains, performance, application barriers, and strategies for further development. Renew Sustain Energy Rev 2012;16:5451–65. http://dx.doi.org/10.1016/j.rser.2012.06.006.

[35] Chiaroni D, Chiesa M, Chiesa V, Cucchiella F, D'Adamo I, Frattini F. An analysis of supply chains in renewable energy industries: a survey in Italy. Green Energy Technol 2015;173:47–71. http://dx.doi.org/10.1007/978-3-319-02696-1_3.

[36] Elia JA, Floudas CA. Energy supply chain optimization of hybrid feedstock processes: a review. Annu Rev Chem Biomol Eng 2014;5:147–79. http://dx.doi.org/10.1146/annurev-chembioeng-060713-040425.

[37] Seay JR, Badurdeen FF. Current trends and directions in achieving sustainability in the biofuel and bioenergy supply chain. Curr Opin Chem Eng 2014;6:55–60. http://dx.doi.org/10.1016/j.coche.2014.09.006.

[38] Hong BH, How BS, Lam HL. Overview of sustainable biomass supply chain: from concept to modelling. Clean Technol Environ Policy 2016;18:2173–94. http://dx.doi.org/10.1007/s10098-016-1155-6.

[39] Goldemberg J, Teixeira Coelho S. Renewable energy – traditional biomass vs. modern biomass. Energy Policy 2004;32:711–4. http://dx.doi.org/10.1016/S0301-4215(02)00340-3.

[40] Lim S, Lee KT. Implementation of biofuels in Malaysian transportation sector towards sustainable development: a case study of international cooperation between Malaysia and Japan. Renew Sustain Energy Rev 2012;16:1790–800. http://dx.doi.org/10.1016/j.rser.2012.01.010.

[41] Kaldellis JK, Apostolou D, Kapsali M, Kondili E. Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. Renew Energy 2016;92:543–56. http://dx.doi.org/10.1016/j.renene.2016.02.018.

[42] Li M, Li X. Investigation of wind characteristics and assessment of wind energy potential for Waterloo region, Canada. Energy Convers Manag 2005;46:3014–33. http://dx.doi.org/10.1016/j.enconman.2005.02.011.

[43] Foley AM, Leahy PG, Marvuglia A, McKeogh EJ. Current methods and advances in forecasting of wind power generation. Renew Energy 2012;37:1–8. http://dx.doi.org/10.1016/j.renene.2011.05.033.

[44] Franco CJ, Ochoa MC, Flórez AM. System dynamics approach to biofuels in colombia. In: Proceedings of 27th international conference of the system dynamics sociecty; 2009. p. 1–11.

[45] Forrester JW. Industrial dynamics. Harv Bus Rev 1958;36:37–66.

[46] Forrester JW. Industrial dynamics—after the first decade. Manag Sci 1968;14:398–415. http://dx.doi.org/10.1287/mnsc.14.7.398.

[47] Forrester JW. System dynamics—a personal view of the first fifty years. Syst Dyn Rev 2007;23:345–58. http://dx.doi.org/10.1002/sdr.382.

[48] Forrester JW. System dynamics—the next fifty years. Syst Dyn Rev 2007;23:359–70. http://dx.doi.org/10.1002/sdr.381.

[49] Bhushi UM, Javalagi CM. System dynamics application to supply chain management: a review In: Proceedings of 2004 IEEE international engineering management conference (IEEE Cat No04CH37574). 3; 2004. p. 1244–48. http://dx.doi.org/10.1109/IEMC.2004.1408893.

[50] Akkermans H, Dellaert N. The rediscovery of industrial dynamics: the contribution of system dynamics to supply chain management in a dynamic and fragmented world. Syst Dyn Rev 2005;21:173–86. http://dx.doi.org/10.1002/sdr.317.

[51] Pagell M, Shevchenko A. Why research in sustainable supply chain management should have no future. J Supply Chain Manag 2014;50:44–55. http://dx.doi.org/10.1111/jscm.12037.

[52] Touboulic A, Walker H. Theories in sustainable supply chain management: a structured literature review. Int J Phys Distrib Logist Manag 2015;45:16–42. http://dx.doi.org/10.1108/IJPDLM-05-2013-0106.

[53] Carter CR, Rogers DS. A framework of sustainable supply chain management: moving toward new theory. Int J Phys Distrib Logist Manag 2008;38:360–87. http://dx.doi.org/10.1108/09600030810882816.

[54] Pagell M, Wu ZH. Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars. J Supply Chain Manag 2009;45:37–56. http://dx.doi.org/10.1111/j.1745-493X.2009.03162.x.

[55] Dey A, LaGuardia P, Srinivasan M. Building sustainability in logistics operations: a research agenda. Manag Res Rev 2011;34:1237–59. http://dx.doi.org/10.1108/01409171111178774.

[56] Vlachos D, Georgiadis P, Iakovou E. A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. Comput Oper Res 2007;34:367–94. http://dx.doi.org/10.1016/j.cor.2005.03.005.

[57] Angerhofer B, Angelides M. System dynamics modelling in supply chain management: research review. 2000 Winter Simul Conf J. 342–51 2000. http://dx.doi.org/10.1109/WSC.2000.899737.

[58] Größler A, Thun J-H, Milling PM. System dynamics as a structural theory in operations management. Prod Oper Manag 2008;17:373–84. http://dx.doi.org/10.3401/poms.1080.0023.

[59] Gold S, Seuring S. Supply chain and logistics issues of bio-energy production. J Clean Prod 2011;19:32–42. http://dx.doi.org/10.1016/j.jclepro.2010.08.009.

[60] ExxonMobil. The outlook for energy: a view to 2040; 2016. p. 1–80. ⟨http://cdn.exxonmobil.com/~/media/global/files/outlook-for-energy/2016/2016-outlook-for-energy.pdf⟩ [Accessed 7 February 2017].

[61] Naill R, Belanger S. A system dynamics model for national energy policy planning. Comput Manag Complex Syst SE – 45 1989;8:423–33. http://dx.doi.org/10.1007/978-3-642-74946-9_45.

[62] Armenia S, Baldoni F, Falsini D, Taibi E. A system dynamics energy model for a sustainable transportation system. In: Proceedings of the 28th international conference of the system dynamics society; 2010.

[63] Nemet A, Klemeš JJ, Duić N, Yan J. Improving sustainability development in energy planning and optimisation. Appl Energy 2016;184:1241–5. http://dx.doi.org/10.1016/j.apenergy.2016.10.111.

[64] Kiani B, Mirzamohammadi S, Hosseini SH. A survey on the role of system dynamics methodology on fossil fuel resources analysis. Int Bus Res 2010;3:84. http://dx.doi.org/10.5539/ibr.v3n3p84.

[65] Robalino-López A, Mena-Nieto A, García-Ramos JE. System dynamics modeling for renewable energy and CO_2 emissions: a case study of Ecuador. Energy Sustain Dev 2014;20:11–20. http://dx.doi.org/10.1016/j.esd.2014.02.001.

[66] Goldemberg J, Mello FFC, Cerri CEP, Davies CA, Cerri CC. Meeting the global demand for biofuels in 2021 through sustainable land use change policy. Energy Policy 2014;69:14–8. http://dx.doi.org/10.1016/j.enpol.2014.02.008.

[67] Budzianowski WM, Postawa K. Total chain integration of sustainable biorefinery systems. Appl Energy 2016;184:1432–46. http://dx.doi.org/10.1016/j.apenergy.2016.06.050.

[68] Alexander A, Walker H, Naim M. Decision theory in sustainable supply chain management: a literature review. Supply Chain Manag Int J 2014;19:504–22. http://dx.doi.org/10.1108/SCM-01-2014-0007.

[69] Saunders M, Lewis P, Thornhill A. Research methods for business students; 2008. http://dx.doi.org/10.1007/s13398-014-0173-7.2.

[70] Dubey R, Gunasekaran A, Papadopoulos T, Childe SJ, Shibin KT, Wamba SF. Sustainable supply chain management: framework and further research directions. J Clean Prod 2016. http://dx.doi.org/10.1016/j.jclepro.2016.03.117.

[71] Ahmad S, Mat Tahar R, Muhammad-Sukki F, Munir AB, Abdul Rahim R. Application of system dynamics approach in electricity sector modelling: a review. Renew Sustain Energy Rev 2016;56:29–37. http://dx.doi.org/10.1016/j.rser.2015.11.034.

[72] Liu X, Zeng M. Renewable energy investment risk evaluation model based on system dynamics. Renew Sustain Energy Rev 2017;73:782–8. http://dx.doi.org/10.1016/j.rser.2017.02.019.

[73] Reddi KR, Li W, Wang B, Moon Y. System dynamics modelling of hybrid renewable energy systems and combined heating and power generator. Int J Sustain Eng 2013;6:31–47. http://dx.doi.org/10.1080/19397038.2012.689781.

[74] Sterman JD. System dynamics modeling: tools for learning in a complex world. Calif Manag Rev 2001;43:8–25. http://dx.doi.org/10.2307/41166098.

[75] Srivastava SK. Green supply-chain management: a state-of-the-art literature review. Int J Manag Rev 2007;9:53–80. http://dx.doi.org/10.1111/j.1468-2370.2007.00202.x.

[76] Bush B, Duffy M, Sandor D, Peterson S. Using system dynamics to model the transition to biofuels in the United States. In: Proceedings of IEEE international conference on system of system engineering; 2008. p. 1–6. http://dx.doi.org/10.1109/SYSOSE.2008.4724136.

[77] Forrester JW. System dynamics, systems thinking, and soft OR. Syst Dyn Rev 1994;10:245–56. http://dx.doi.org/10.1002/sdr.4260100211.