MODELLING THE DYNAMICS OF RENEWABLE ENERGY TECHNOLOGIES: A REVIEW OF PAST EXPERIENCE AND FUTURE OPPORTUNITIES

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ABSTRACT

This paper reviews the use of formal quantitative models, i.e. simulation modeling that have been used to explore and explain emergent dynamics of the development and diffusion of renewable energy technologies under three different systems frameworks namely the *technological innovation system (TIS)*, *innovation ecosystems (IE)* and *multi-level perspective (MLP)*. Specifically, we aim to explore the main similarities and differences on the use of these three systems frameworks by using the following analytical dimensions: i) core elements, building blocks and organizing principles; ii) dynamics and iii) modelling approaches and applications. As main result, we find the dominant use of system dynamics modeling and agent-based modeling on all three frameworks, however, with differences in their goals, modelling purpose and approaches. The paper concludes by showing possible pathways to integration of these frameworks for modeling purposes and future research opportunities.

Keywords: sustainability transitions; socio-technical systems; renewable energy technologies; clean technologies; system dynamics; agent-based modelling.

INTRODUCTION

Renewable Energy Technologies (RET) have been hailed as the most promising mechanisms to cut emissions and to develop more sustainable societies. In developing countries, for instance, RET may offer off-grid electricity access to rural communities, cleaner means of transportation in urban regions, lower costs of energy for both citizens and industry and a reduction in natural resource exploitation and negative impacts on the environment (Ellabban et al., 2014; Pfeiffer and Mulder, 2013).

The literature addressing the diffusion of renewable energy technologies has been mostly of a qualitative nature. These studies tend to providing in-depth intuitive understanding of particular cases and remain highly descriptive but fail to account for the non-linear dynamics of innovation which are embedded in them (Holtz, 2011).

Along this line of reasoning, several authors have also proposed the use of formal quantitative methods, such as simulation modeling to help explore and explain emergent dynamics of the development and diffusion of RET - especially on macro-level and micro-level structures and behavior within socio-technical systems (Holtz, 2011; Holtz et al., 2015; Landini et al., 2017; Malerba et al., 2008).

Thus, the main aim of this paper is to explore to what extent simulation modelling has been previously used to study and analyze RET diffusion as well as to point out future research opportunities in this domain. In order to do so, we review the literature on three systems frameworks, namely, the technological innovation system perspective, the innovation ecosystems perspective and the multi-level perspective, to classify and to identify commonalities and complementarities between them and to explore potential pathways to integration. Finally, we specifically focus on how these three frameworks may allow us to have an improved understanding of RET dynamics.

This paper therefore contributes to the existing body of literature by exploring three relevant systems frameworks and how they could be used in an integrative way, specifically by making progress towards simulation modeling of the dynamics of innovation in the RETs domain. Moreover, the idea of developing formal simulation models, based on the building blocks of these frameworks, may be of importance in order to better understand RETs development and diffusion in especially Developing Countries.

METHODS

As noted in the introduction, the authors embarked on an in-depth review on the literature on the *innovation system*, *innovation ecosystems* and *multi-level perspective* frameworks, specifically scrutinizing the literature and its contribution to the application area of the modeling of RET diffusion. The analysis was aimed at i) identifying the core elements, main building blocks and organizing principles; ii) dynamics and iii) modelling, for the three frameworks, and to consider commonalities and complementarities between them and to explore potential pathways to integration.

In order to do so, the authors queried three databases, namely Scopus, Science Direct and Emerald, in order to systematically search for studies with simulation modeling applications within the three frameworks. The following table summarizes the number of papers and studies that were studied and explored for this paper.

Table 1: Summary of systematic search for modeling studies

Search terms	Articles retrieved	Relevant articles identified
(“modelling”, “technological	40 papers were retrieved and reviewed	2 publications were

innovation system") OR ("modeling", "technological innovation system")	for relevance to the topic	analyzed in-depth
("modelling", "innovation ecosystem") OR ("modeling", "innovation ecosystem")	44 papers were retrieved and reviewed for relevance to the topic	13 articles were analyzed in-depth
("modelling", "multi-level perspective") OR ("modeling", "multi-level perspective")	72 papers were retrieved and reviewed for relevance to the topic	7 articles were analyzed in-depth

Furthermore, the authors explored the simulation modelling techniques used as well as the nature of problems addressed in these models. Towards developing some conclusions regarding the analysis, the authors extracted insights regarding useful conceptual approaches and to what extent the three frameworks are complementary for future modelling exercises (See Table 2)

Table 2: Core factors considered in the systematic analysis of modeling studies

Paper level analysis	Conclusions
• Model type • Paper name • Domain • Theoretical foundations • Model purpose	• Core elements Key building blocks and organizing concepts and principles (or subsystems) • Core theoretical foundations • Simulation Modelling techniques used • Useful conceptual approaches for future modelling exercises

MODELLING RENEWABLE ENERGY TECHNOLOGY DYNAMICS

Technological innovation systems

Core elements, building blocks and organizing principles

Previous literature within the IS domain has pointed out the relative disagreement between IS scholars in terms of what are the components of an innovation system, which activities comprise the system, and which learning processes are relevant (Edquist, 2005). However, two major approaches have emerged: the component-based approach and the activities-based or functions-based approach.

The component-based approach allows for structural analysis, by identifying the key actors, institutions, infrastructure, networks and the learning flows and knowledge stocks linking them. The usefulness of the components based approach lies in that it allows for an improved understanding of the role of innovation systems components namely actors, learning, networks and linkages, infrastructure and institution in the innovation process (Bergek et al., 2008)

On the other hand, the activities-based or functions-based stream consider systems functions – or key activities – and various dynamics that need to be stimulated in the system. The functions based approach (which was developed within the TIS literature) is helpful in understanding the dynamic processes of systems components towards performing systems goals through these functions (Haddad and Uriona, 2017; Hekkert et al., 2007). These functions include entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, mobilisation of resources and the creation of legitimacy (Alkemade and Hekkert, 2009; Bergek et al., 2008; Carlsson et al., 2002; Hekkert et al., 2007; Smits and Kuhlmann, 2004; Tigabu et al., 2015; van der Hilst, 2012; Wieczorek and Hekkert, 2012).

Also, in terms of organizing principles, the IS literature is based on the notion that traditional neoclassical economics cannot explain market or systems failures. This is especially important in the Developing Countries domain, whereby the weak institutional framework inhibits the market to self-regulate in an efficient manner or for systems to create opportunities to innovate. The notion of an innovation system is, thus, the need to understand how different agents interact with each other, forming networks within the institutional framework, in a systemic way. Furthermore, learning has traditionally been a core focus of IS literature and has focused on a range of capabilities that need to be developed in systems actors namely: selective or strategic ability, organizational ability, technical ability, learning or adaptive ability (Metcalfe, 2005; Metcalfe and Ramlogan, 2008).

TIS Dynamics

The IS framework has been criticized to be very static. Analytical frameworks, such as the ‘functions’ of innovation systems tend to consider the dynamic patterns of the system by looking at how it changes and evolves over time (Hekkert et al., 2007). Also, approaches such as ‘innovation system foresight’ have tried to integrate forward-looking techniques within the innovation system, in order to develop more effective and efficient innovation policy (Andersen and Andersen, 2014; Haddad and Uriona, 2017). However, such approaches are still heavily grounded on a qualitative perspective, offering high descriptive power but lacking an analytical one. The literature, in this sense, has pointed out the need to develop more studies using formal models in general and simulation models in particular (Lee and von Tunzelmann, 2005).

With regard to the functions-based approach, the authors suggest that future work may lead to unraveling the complex dynamic behavior of socio-technical systems, by analyzing each function, not in isolation, but in conjunction, and by describing how the functions influence each other, forming feedback loops of cumulative causation (Suurs and Hekkert, 2009). That is, the individual performance of a function may influence the performance of another, and in turn, may influence the systems overall performance. To this end, Table 1 presents a summary of each of the seven functions, as proposed by Hekkert et al. (2007).

TIS modelling

Within the broad literature of innovation systems, simulation modelling has been mostly used to describe the behavior of particular agents and their interactions, through bottom-up agent-based modelling; and the top-down modeling of several processes through the system dynamics methodology.

Models under the ABM tradition have tended to formalize micro-level social mechanisms generating macro-level behavior and reproducing various stylized facts concerning innovation (Watts and Gilbert, 2014). Exemplary studies include the work by Nelson and Winter (1982) and the set of evolutionary models of technical change, inspired by it (Windrum, 1999). A recent stream has put forth the so-called history friendly models, which seek to serve as integrative frameworks between formal theory, empirical evidence and ABM (Garavaglia, 2010; Landini et al., 2017).

Models under the system dynamics tradition, on the other hand, have tended to look for both, formal and quasi-formal mechanisms within the innovation system. Some of the key processes modelled with system dynamics are: the dynamics of R&D (Galanakis, 2006; Lee and von Tunzelmann, 2005; Samara et al., 2012); innovation diffusion and technology adoption (Janszen and Degenaars, 1998; Milling, 2002); knowledge creation and absorption (Grobbelaar, 2006; Mora-Luna and Davidsen, 2006; Tayaran, 2011); the dynamics of science and technology (Castellacci and Hamza, 2015; Rodriguez and Navarro-Chávez, 2015); learning processes (Uriona et al. (2015)); and the dynamics of agglomeration (Dangelico et al., 2010).

With respect to quantitative modelling of technological innovation systems and their functions, the literature remains surprisingly sparse. To the knowledge of the authors only two published studies have moved further in modelling some aspects of a TIS. First, the paper by Walrave and Raven

(2016) proposes an integrative framework between the functions of innovation systems, and the multi-level perspective, whereby the functions influence each other and create cumulative reinforcing and balancing feedbacks at the niche and regime levels, based on the notion of the motors of innovation (Suurs and Hekkert, 2009). Second, the dissertation by Ahmadian (2008), whereby the author develops several system dynamics models – of conceptual nature – to showcase how radical innovations and technologies compete against incumbent ones. More specifically, Ahmadian (2008) develops a modeling structure for the legitimacy function (F7) based on social interaction (i.e. word-of-mouth), advertising efforts and the installed base of adopters.

Multi-level perspective

Core elements, building blocks and organizing principles

The Multi-level perspective (MLP) states that technological change for radical technologies (such as renewable energy technologies) takes place at three conceptually different levels (the niche, the socio-technical regime and the landscape). The niche represents the micro-level, referring to the protected spaces or incubating rooms, in which emerging technologies grow or develop isolated from the selection mechanisms of the 'normal' market (Geels, 2004; Markard and Truffer, 2008).

The socio-technical regime represents the meso-level, characterized by established institutional set-ups (norms, regulations, etc.), knowledge base, products and technologies. And finally, the landscape represents the macro-level which might put pressure on the socio-technical regime and open windows of opportunities for niches to break through but is hardly affected by them (Markard et al., 2012).

As was the case for the innovation system approach, the multi-level perspective draws upon evolutionary economics (Nelson and Winter, 1982) but it incorporates the theoretical framework of history and sociology of technology as well (Hughes, 1987) highlighting the embeddedness of technology in a larger socio-technical system (Markard et al., 2012).

In this sense, all three levels interact and evolve over time, where new radical technologies, such as solar PV or wind turbines, compete against incumbent technologies in a sort of natural selection process. To some scholars within this field, it means new radical technologies should be protected at first, within the niche and therefore, the 'strategic niche management' stream has dealt with investigating how niches might grow, stabilize or decline as well as looking for means to create and support such niches (Kemp et al., 1998; Schot and Geels, 2008).

MLP dynamics

The multi-level perspective in essence is a dynamic framework, since it characterizes how the three levels interact through time beginning at the niche-level and going up through the socio-technical regime and lastly to the landscape. At the niche level, core dynamic processes are experimentation and learning *(Späth and Rohracher, 2012)* which lead to the formation of networks of actors supporting the technology. As the networks become stronger, experimentation leads to dominant designs, which enter the regime.

At the regime level, the industry supply chain, the markets and the existent technologies are in dynamic equilibrium, until a new technology breaks through and creates disequilibrium dynamics, forcing actors, groups (both social and organizational) to adjust to the new configurations (Geels, 2011). The institutions (formal, cognitive and of normative type) which guide actors behavior have to adjust as well (van Bree et al., 2010).

The regime receives, as well, influence from the landscape, which puts pressures on the current configurations of the regime, by opening up windows of opportunity for new technologies or radical innovations. Eventually, the new regime configuration – the outcome of the introduction of radical innovations – may influence the landscape as well, although with a longer timing in terms of dynamics.

How the three levels might evolve through time depends on the interdependencies between them and therefore, the literature is assertive in stating different outcomes are possible. Some typologies, however, have been proposed previously, namely, transition pathways, which aim at describing how the socio-technical system dynamics will unfold in the long-term (Foxon et al., 2010).

While the multi-level perspective describes elegantly the dynamics behind complex socio-technical systems, some shortcomings were pointed out in the literature[1], especially when it comes to its lack of operationalization (Geels, 2011; Li and Strachan, 2016). Perhaps, in this sense, simulation modelling can contribute in developing operational means to implement policy recommendations based on the use of the MLP.

MLP modelling

So far, little is known of simulation modelling applications in the MLP domain since this approach emerged from the fields of history and sociology of technology. In this sense, most of the previous work, within the MLP literature has been of qualitative nature. However, recent work has highlighted the need to develop formal models as a means to reinforce the analytical power of the MLP (Holtz, 2011; Holtz et al., 2015).

Within the MLP literature, the authors have found seven articles using simulation modeling for different purposes that qualify as theoretical and

[1] The whole set of shortcomings are: i) its lack of agency; ii) operationalization; iii) bias towards bottom-up change models; iv) epistemology and explanatory style; v) methodology; vi) socio-technical landscape as residual category; and vii) flat ontologies versus hierarchical levels Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1, 24-40.

empirical applications (See Table 3). Three types of modelling methodologies have been found, namely agent based modelling, systems dynamics and differential equations. In particular, system dynamics modelling have been the most often utilized methodology, with five out of the seven paper analysed. Some high level comments on the various models are presented below.

Papachristos (2011) highlights the use of system dynamics as a suitable one for representing the nonlinear dynamic processes, which are characteristic of sociotechnical transitions and MLP in particular. The model developed by Papachristos (2011) shows how a substitution pathway is developed by cause-effect relationships in all three levels of the MLP: the landscape, the sociotechnical regime and the niche.

Auvinen et al. (2014) propose a comprehensive process to support strategic decision making, using as conceptual framework the MLP and system dynamics, foresight and road mapping as tools to develop future scenarios and uses as case study the transition to clean transportation in Finland.

Li and Strachan (2016) on the other hand, develop a more ambitious system dynamics model – named BLUE – which includes a large set of key variables that influence energy use and emissions as an energy transitions unfolds, namely, the energy supply as well as the residential, commercial, industrial and transport sectors, which represent energy demand. The model is arranged according to the three levels of the MLP.

Papachristos and Adamides (2016) develop a system dynamics model to help explain how a novel socio-technical transition occurred and to identify the cause-effect relationships which are often beyond extrapolating trends and behaviors. They propose a method which is composed by a cycle of abduction, deduction and induction, which helps in identifying the mechanisms and interactions that took place in the three levels of the MLP. They use the functional foods case to illustrate how such mechanisms can be observed at the landscape, regime and niche levels.

The last of the articles using system dynamics is the work by Walrave and Raven (2016), which uses system dynamics modeling to develop a formal model of the functions of technological innovation systems (Hekkert and Negro, 2009) embedded in the niche and socio-technical regime levels of the MLP. The authors illustrate its use through a generic case, in which the functioning of the innovation system affects and is affected by the interactions with other variables and functions from the niche and sociotechnical regime levels.

Finally, two papers use agent-based modelling (Chevarria and Pedroso, 2016) and differential equations (Mercure, 2015) to model MLP. The first one develops an ABM model in order to represent how heterogeneous agents interact at the niche and regime levels and uses the case of wind farms construction as case study. The second one develops a Lotka-Volterra type model to derive the behavior of technological change assuming technology behaves as a living population with birth, deaths and choice processes.

Differently from the literature on innovation systems and innovation ecosystems, no core dynamics were found in the MLP models as all of them are applied to single specific contexts with only one commonality, which is the use of the MLP as theoretical framework. Perhaps, one of the key criticisms, in this sense, is the lack of common components or variables, which could be replicated and applied in future works.

Table 3: Models of innovation from the multi-level perspective

Model Type	Paper Name	Domain	Theory	Model Purpose
System Dynamics	Modelling the dynamics of technological innovation systems (Walrave and Raven, 2016)	General	MLP, TIS and the motors of innovation	To integrate MLP and TIS under SD
System Dynamics	A retroductive systems-based methodology for socio-technical transitions research (Papachristos and Adamides, 2016)	Functional Foods	Transitions Literature	It proposes a retroductive systems-based methodology. The methodology relies on qualitative case study development and quantitative simulation modelling
System Dynamics	Modelling energy transitions for climate targets under landscape and actor inertia (Li and Strachan, 2016)	UK energy system	Transitions Literature	To fully represent behavioral assumptions not previously taken into account by energy models
Agent-based Modelling	Modeling technological transitions through Multiagent Systems (Chevarria and Pedroso, 2016)	MLP and ABM	Complex Adaptive Systems	To develop a ABM model for socio-technical transitions

Differential Equations	An age structured demographic theory of technological change (Mercure, 2015)	General	Innovation Diffusion	To develop a model of technology competition based on demographic principles and Lotka-Volterra
System Dynamics	Process supporting strategic decision-making in systemic transitions (Auvinen et al., 2014)	Transport Sector	Strategic Foresight	To introduce a process for supporting strategic decision-making and policy planning in systemic transitions related to grand challenges such as climate change
System Dynamics	A system dynamics model of socio-technical regime transitions (Papachristos, 2011)	General	Transitions Literature	To assess a particular MLP transition pathway, namely regime substitution.

Innovation ecosystems

Core elements, building blocks and organizing principles

A system – as with the innovation perspective refers to various components that interact with each other towards a common goal or purpose, where ecosystem perspective leans towards considering the systems as a complex adaptive system. The innovation ecosystem perspective has been adopted in a business context and maintains that certain actors create whole eco-systems usually around certain products or some platform (Iansiti and Levien, 2004; Moore, 1993; Oh et al., 2016).

Mostly described as a *profit-driven systems* a focus on *companies, technologies and platforms* has been a trend in the published literature on innovation ecosystems. The ecosystem's evolution depends on the interconnectedness and interdependence between actors with various roles identified in the literature such as: initiators that develop the eco-system, specialists that add value to a central platform, the adopter that follow the initiator and co-develop the product/platform (Tucker et al., 2013).

With innovation as the goal or focus of the ecosystem in all cases ecosystem boundaries differ widely between geographical scope (local vs.

regional or national vs. global); temporal scale (past to future or static snapshot vs. dynamic interaction); permeability (open vs. closed); or types of flow (knowledge, value, material). The literature also distinguishes between various types of eco-systems namely corporate innovation ecosystems, regional and national, digital, city-based, high tech, SME centered ecosystems, incubators and accelerators and university based ecosystems (Ritala and Almpanopoulou, 2017).

Ecosystem leaders often establish the ecosystem around a platform such as a technological platform, supply-chain platforms or industry platforms with leadership provided through the concertation and orchestration of such platforms (van Rooyen *et al*., 2013). Platform thinking has become central to the idea of nurturing and developing innovation ecosystems. As an organising principle, Innovation Platforms have been applied in a vast range of areas to facilitate multi-stakeholder engagement and innovation (Bullinger *et al*., 2012; Shaw and Allen, 2016).

In spite of the type of platform, multi-stakeholder engagement help stakeholders to realise their interdependence and collective action in problem solving and to reach stated objectives. Platforms also in general put a strong emphasis on a systematic and iterative process of learning through reflection. Innovation platforms also serve as a space to negotiate power dynamics (Ngwenya and Hagmann, 2011) and this function combined with exchange of knowledge and learning compliments the capacity to innovate amongst the actors. This is achieved by continuously identifying and prioritizing problems and opportunities and experimenting with social and technical options (Dror *et al*., 2015).

IE dynamics

A central concept to the concertation and coordination of an eco-systems is complexity theory which have been used to explain the process of emergence of ecosystems and interaction around a principle of self-organization (Gawer and Cusumano, 2014). This makes the framework useful as it goes to some length to help include the evolutionary features of interactions between individuals, their relationships and relations to the environment also including issues such as open innovation and the development of capabilities in actors (Durst and Poutanen, 2013). What is specifically useful in terms of the ecosystems perspective is the issue of “portfolio thinking” in a wide range of offerings and processes to create value to meet diverse stakeholder needs (Nambisan and Zahra, 2016; Weil et al., 2014).

Furthermore, the innovation eco-system structure attempts to make some distinction between innovation events and innovation structures which include economic agents and the relations between them and non-economic issues such as technology, institutions and culture (Mercan and Götkas, 2011). Separated into two economies the tension between the research economy and the commercial economy have been argued to be the drivers of the evolution of the system (Oh et al., 2016).

Strategic consideration for the management of ecosystems have been described in the literature with considerations such as value creation dynamics, ecosystem architectures and various strategic focus levels (Autio and Thomas, 2014). An improved understanding of the value creation dynamics also provides insight into the approaches and way in which ecosystems can be managed and developed.

As far as value creation dynamics are concerned the order and sequence of how such value creation take place in a networked system, and how value is appropriated by various ecosystem participants, migration control; and value externalities is of interest (Autio and Thomas, 2014). A number of studies consider the management of ecosystems governance considering risk management, conflict of interest, boundary resources management of technology and human resources (Durst and Poutanen, 2013). Here the orchestration process is in particular focused on and takes place often by management of three major tasks 1) the ecosystem leader and facilitate knowledge mobility between network members 2) the process of innovation appropriability concerned with the fair distribution of value in the system with 3) the management of network stability for ensuring a nonnegative growth rates of the network (Catalina and Marin, 2012; Berk *et al*., 2016)

Technological architecture, or the design principles of shared technological resources and platforms often determine which actors will be able to connect to the innovation ecosystem and in which roles. Here Autio and Thomas (2014) distinguish between 1) activity architecture which defines the composition and structure of the innovation ecosystem that may emerge around the core platform 2) Value architecture which describes value dynamic, as defined by the interplay between technological architecture and 3) technology architecture that entails the design and principles of shared resources (Autio and Thomas, 2014)

IE modelling

Although articles of the modeling of innovation ecosystems remain sparse – the authors have identified 13 published studies from the literature that qualify as theoretical and empirical models of innovation ecosystems. Some high-level comments on the various models are considered below (See Table 4).

The author have identified seven types of models of innovation ecosystems from the literature namely agent based modelling, game theory, Genetic Algorithm (GA), logistics equations, networking models, structural equation modeling and systems dynamics. As described in the theoretical literature of IE, complexity theory is a central scientific domain that is widely used in these models. In particular ABM models tend to be based on theoretical basis of complex adaptive systems, network effects and multi-agent systems. The second most implemented type of model namely network models are based on concepts such as network analysis, actor-network theory principles. This is also closely related to the comment that ecosystem acknowledge the networked and systemic nature of innovation.

Core dynamics that have been modelled through these 13 models reviewed include four major focal areas namely 1) Collaboration and development 2) Learning; 3) Market Dynamics 4) Innovation and diffusion dynamics. In our sample the models that explore collaboration and development focus on co-learning, and co-innovation dimensions of collaborative product development (Arsenyan et al., 2015); industrial ecology and biological co-evolution in the automotive domain (Wang and Liu, 2016) a symbiotic evolution model to analyze the symbiotic modes and dynamic equilibrium of mobile internet platform innovation ecosystems (Yao and Zhou, 2016) and public sector innovation and co-creation with a focus on the Brazilian Federal Government (Santos *et al*., 2015). One model had a focus on *learning* at the core with informal learning environments; communities of practice (Aramo-Immonen *et al*., 2016). The issue of *market dynamics* consider the process to affect the adoption of technology, linking the evolution of the innovation ecosystem to market dynamics and dominant designs emerge (Weil, Sabhlok and Cooney, 2014). The final category namely *Innovation and diffusion* focused model consider innovation diffusion, co-evolution, innovation and standardization, and technological innovation systems (Groesser, 2014)

Of particular interest there were three platform related models in the area of gaming consoles and platform economies (Huotari *et al*., 2015), Platform ecosystem considering Product Platforms and Content Platforms (Lee and Hwang, 2016) and mobile internet platform (Yao and Zhou, 2016).

Application to the Renewable Energy domain remain sparse with modelling approaches used in eco-systems and their implications for innovation management in transitions highlighted in the literature. We have identified in particular two papers that focus on smart grid development and how ecosystems develop and drive transitions (Ginsberg *et al*., 2010; Kirsi *et al*., 2016).

In conclusion for this section, simulation modeling from the innovation ecosystem perspective holds exciting prospects to further explore the dynamics of innovation with a lot of potential to evolve from mostly descriptive to predictive approaches and in particular the concept of innovation platforms as an organizing principle for innovation activity.

Table 4: Models of innovation from the innovation ecosystem perspective

Model type	Paper name	Domain	Theory	Model purpose
Agent based modelling	Role of entrepreneurial support for networking in innovation ecosystems: An agent based approach (Akbas *et al*., 2016);	Regional Technological Innovation Ecosystem	Complex adaptive systems	Model the effect of various forms of entrepreneurial support on the system; this includes financial; resources and networking support; network support is modeled through the vision radius of the agents.
Agent based modelling	Effective and sustainable cooperation between start-ups, venture investors and corporations (Akhmadeev and Manakhov, 2015)	Cooperation and investment in startups; investors	Agent-based modelling, decentralized systems, venture investments, mergers and acquisitions, innovation development	Process of innovation investment; analyzing results of merger and acquisition processes.
Agent based modelling	Winner does not take all: Selective attention and local bias in platform-based markets (Huotari *et al*., 2015)	Gaming consoles; platform economies	Network effects	Model of gaming console platform economies exploring relationship between installed base and winner take all outcomes; model consumer behavior and comparison to behavior of empirical data from Sony's PlayStation 3 and Microsoft's Xbox 360.
Agent based modelli	A Multi-Agent System model framework of Regional Technology	Regional Technological Innovation	Multi-Agent System (MAS) in complex system	Considered advantages of Multi-Agent System (MAS) in complex system research, explores the theory of modeling the RTIE in MAS method.

ng	Innovation Ecosystem (Tie and Lei, 2014)	Ecosystem	research	Conceptualisation and relation of Corporation Agent, Innovation Resources Agent, Regulation Agent.
Game theory	Modeling collaboration formation with a game theory approach (Arsenyan, Buyukozkan and Feyzioglu, 2015)	Collaborative formation; collaborative product development		This paper proposes a mathematical model integrating trust, coordination, co-learning, and co-innovation dimensions of Collaborative Product Development.
Genetic algorith m (GA)	The influence of giant platform on content diversity (Lee and Hwang, 2016)	Platform ecosystem; Product Platforms and Content Platforms	Ecosystem Layer Model (ELM); evolutionary mechanisms on platforms	Explores issue of decreasing content diversity and how product platforms and content platforms evolve in the platform ecosystem, suggests a model to reflect the dynamics of their relationship based on genetic algorithm model.
Logistic s equatio n	A Novel Modelling Study on Innovation Co-Evolution Mechanisms of Automobile Industrial Clusters(Wang and Liu, 2016)	Automotive ecosystem	industrial ecology and biological co-evolution	Introduces ecology and the theory of co-evolution into the research of the innovation system of automobile industrial cluster and reveals dynamic mechanism and systematic evolutionary law of the innovation ecosystem of automobile industrial cluster.
Logistic s equatio n	The dynamic equilibrium and simulation of mobile internet platform innovation ecosystem: symbiotic evolution model (Yao and Zhou, 2016)	Mobile internet platform innovation ecosystem	symbiosis theory perspective; business ecosystem theory; Innovation ecosystem,	The purpose of this paper is to build a symbiotic evolution model to analyze the symbiotic modes and dynamic equilibrium of mobile internet platform innovation ecosystem (MIPIE) in order to explore its evolutionary path.

			Mobile internet platform, Symbiotic evolution	
Networ k	Visualizing informal learning behavior from conference participants' Twitter data with the Ostinato Model (Aramo-Immonen *et al*., 2016)	Network analysis; learning; informal learning environments; learning behaviour	Network analysis; learning; informal learning environments; communities of practice	Explore informal learning behavior in the project context, especially by analyzing and visualizing informal learning behavior from Twitter data using the Ostinato Model.
Networ k	An actor-network perspective on evaluating the R&D linking efficiency of innovation ecosystems (Chen and Hung, 2016)	R&D efficiency; Research evaluation; actor-network theory	Actor-network theory	Evaluate the relative R&D efficiency across the global twenty-five countries.
Networ k	The dynamics of innovation ecosystems: A case study of the US biofuel market (Weil, Sabhlok and Cooney, 2014)	Biofuels ecosystem;	ecosystems; innovation systems	Analyzing how the dynamics of markets affect the adoption of technology; Linking the evolution of the innovation ecosystem to the market dynamics; Showing how these interacting dynamics affect emergence of a dominant design.
Structur al Equatio n	Collaborative innovation in the public sector a case of the Brazilian Federal Government (Santos *et al*.,	Public sector innovation and co-creation	Co-creation; public sector innovation; Innovation	a) Propose and validate a theoretical model that describes the elements of public sector collaborative innovations a collaborative public sector innovation model in the Brazilian Federal

Modeling	2015)		ecosystem; governance models; networks	Government context.
System Dynamics	Co-evolution of legal and voluntary standards: Development of energy efficiency in Swiss residential building codes (Groesser, 2014)	Energy efficiency, residential building codes	Innovation diffusion, co-evolution, innovation and standardization, and technological innovation systems	Explore the feedback dynamics between innovation, diffusion, and standardization.

COMPARATIVE ANALYSIS OF THE FRAMEWORKS

We consider a comparative analysis of the three frameworks and models reviewed. To this end, all three approaches have related but different concepts that may provide insight into how to improve the quantitative modeling of TIS. We have summarized the comparative analysis in Error: Reference source not found and provide a qualitative discussion of this comparison and conclusion below.

Table 5: Comparative analysis of innovation systems; ecosystems and MLP innovation models.

	Innovation systems	Ecosystems	MLP
Core elements Key building blocks and organizing concepts and principles (or subsystems)	Structural approach considers components of the system (actors, linkages and institutions); Functions: key activities which are important for the innovation system to perform adequately;	Actors: initiators, specialists, adopters that co-develop the product/platform Economic agents and relations between; non-economic issues such as technology, institutions and culture Management of ecosystems: value creation dynamics, ecosystem architectures and various strategic focus levels Participant symbiosis, institutional stability Platforms and platform economies	Main elements are the niche (micro-level), the socio-technical regime (meso-level) and the landscape (macro-level).

Core theoretical foundations	Evolutionary theory; Industrial districts, agglomeration Neo-Schumpeterian theory	Evolutionary economics Complex adaptive systems; complexity theory, emergence;	Evolutionary economics; history and sociology of technology
Simulation Modeling techniques used	With respect to IS in general: ABM and system dynamics With respect to TIS: system dynamics;	Agent based modelling, game theory, Genetic Algorithm (GA), logistics equations, networking models, structural equation modeling and systems dynamics	System Dynamics, agent based modeling, Differential Equations (Lotka-Volterra)
Useful conceptual approaches for future modelling exercises	Functions approach is useful to unpack dynamics of innovation systems Learning, knowledge creation and absorptive capacities are recognized as a main mechanisms; Evolutionary principles of technological that has been modelled provide insight in innovation diffusion and adoption	Dynamics of 1) Collaboration and development 2) Learning 3) Market Dynamics 4) Innovation and diffusion dynamics 5) value creation 6) platform ecosystem dynamics Value creation dynamics; Value creation architectures; Strategic conceptualizations of technology, economy, behavioral and institutional	Integrates Micro level, Meso and Macro-level approaches Transition pathways and transition dynamics are described and developed Experimentation and learning

All three approaches reviewed have evolutionary economic theory as a fundamental theoretical foundation. All three approaches have learning and the dynamics of learning as an important part of how these systems evolve. All three frameworks reviewed have a number of models that have been implemented on the agent level with its roots in micro-level foundations of the behavior of agents in a system. Consequently many of these models were implemented as network models and agent based models. System Dynamics modelling has also been utilised for all three framework reviewed but remains thin on the ground.

In the process of exploring modelling studies that utilize these three framework the question remains: How do these framework complement each other and how can commonalities of the frameworks contribute to improved quantitative modeling approaches to model RETs? Comparing the contribution of the three frameworks is therefore useful for exploring what next generation innovation systems models may look like.

The Technological Innovation Systems perspective has been utilized in very few models up to date. This is surprising as the TIS is arguably one of the most widely used innovation systems perspectives utilised by RET policy makers. It may however be explained by a lack of attempts to unpack systems functions and how these relate to the systems view of innovation; also the difficulty of establishing appropriate boundaries and levels of aggregation for modelling various components in the system and how they interact to perform systems functions. This furthermore also takes place on many levels and are affected by macro, meso and micro factors and environments – which are typically difficult to define not to even mention quantify. It is then in this area that we also considered the MLP perspective and how that may help illuminate improved model structures.

The Innovation Ecosystems perspective seems to be applied mostly on the industry level and has found wider appeal and application than the IS perspective within the business community. Of particular interest to the eco-system perspective is the recognition of technology platforms and platform economies as the basis of organizing these systems. It also provides an additional insight in terms of the dynamics of ecosystems where the concept of value creation, dynamics ecosystem architectures, concertation of ecosystem activities and strategic focus levels have proven useful. In a number of cases the unit of analysis in terms of understanding the behavior of economic agents and focus area of the applied models with innovation ecosystems that are heavily based on complex adaptive system and complexity theory.

The innovation ecosystem framework offers three refreshing perspectives for innovation systems modelling. First, on the importance of the private sector, as the coordinating agent nurturing radical innovations, which could be very well conceptually integrated within the niche-level and regime-level of the MLP and also, within the TIS functions. Second, there is a focus on profit-driven systems, which can conceptually incorporate understudied motives behind RET diffusion, such as policies guaranteeing wind or solar PV capacity expansion in the forthcoming years, that may ensure private sector investments. And finally, the perspective of platforms (instead of the supply chain concept) whereby positive externalities are produced when radical innovations such as RETs. Here the platform concept helps to understand how innovations are developed and commercialized in conjunction with third-party goods and services, enhancing the overall industry attractiveness, reducing costs through economies of scale and thus, increasing the installed base of users. Furthermore the platform perspective allows for the exploration of some “hard” issues such as architectures and how those should be designed to facilitate ecosystem to evolve around a platform and how platforms evolve over time to become open platforms for innovation where ecosystem participants co-evolve and develop complementary products and services.

As alluded to earlier, the MLP’s usefulness lies in that it links up micro-level foundations (niches) with the meso-level (socio-technical regime) and the macro-level (landscape). This has important implications for modeling approaches to link up explanatory factors for the behavior of individual agents and how the interaction of agents take place in relation to policy and industry contexts. None of the other two approaches readily provide insight in linking these levels; however the development of causal linkages and establishing relationship within this framework remains vague with most studies to date that remain descriptive. On a more practical note, this may have further implications for linking up agent based modelling and system dynamics models (that are usually on an aggregate level)

IN CONCLUSION: FUTURE WORK AND OPPORTUNITIES

This paper’s main objective was to explore to what extent simulation modelling has been previously used to study and analyze RET diffusion as well as to point out future research opportunities by means of a literature review. In order to do so, we explored three different frameworks (IS, IE, MLP) and looked for commonalities and complementarities and possible pathways to integration.

Through the comparative analysis, it can be concluded that although the three frameworks have some theoretical foundation in common (specifically evolutionary economic theory) their formulation has resulted in very different levels of focus and formulations of system structures and dynamics. This may be inter alia attributable to a matter of perspective, where the IS and MLP approaches have mostly been utilized by policy makers and the IE perspective mostly from that of lead firms in a technology platform economy.

Future research opportunities to push forward the quantitative modeling domain around RETs may benefit from the integration and adaptation of concepts from these three frameworks. However much more in-depth unpacking of the micro foundations of the dynamics experienced in the these systems will be the objective of such modelling studies and not the aggregate effects achieved and often described in systems analysis.

This may also include the development of *modular approaches* to start to develop systems models from the bottom up (e.g. for each one of the TIS systems functions). Here examples of this may include the TIS perspective to unpack functions individually; from MLP perspective to consider how various levels integrated in models may be formulated to effect each other; from IE perspective the dynamics around platforms and platform coordinators and leaders.

With the view of providing *explanatory value*, hybrid approaches to systems modelling may include various levels in the model from making use of ABM dynamics and formulations on the micro level and on aggregate may explain some trends that are viewed on the meso and macro level (the MLP perspective). This may allow for high-level decision rules to also be tested on expected behaviors on the agent level. *Improved design and testing environments* can thus be created for better understanding of the fundamental dynamics of systems to consider the design of systemic instruments that will bring about change on the systems level.

Even though hybrid formulations of innovation systems models may be very useful such endeavors must be approached carefully as a lot of extra complexity may be added to modeling studies. This therefore needs to be carefully balanced with the extent to which new insights are gained regarding fundamental dynamics that is brought about by actors and their activities and inter-level systemic influences as observed in the MLP.

Also worth considering, models aimed at being utilized as *forecasting models* rely a lot on historical time series data that is not always available on the right level and in the right format. What is more is that although innovation and R&D data it is gathered on an agent level it often only is meaningfully interpreted on an aggregate level or in terms of trends. This raises the future issue of how to improve data gathering of time series data and ensue its availability which will have major implications for the validation of models.

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