CREATING A RENEWABLE ENERGY ECOSYSTEM: EVIDENCE FROM INDIA

DR. GITA SURIE
Robert B. Willumstad School of Business, Adelphi University, USA
surie@adelphi.edu

ABSTRACT

This paper develops a conceptual framework for the establishment and evolution of new industrial ecosystems drawing on theories of biological ecosystems (Vihervaara et al., 2010), industrial ecosystems and national systems of innovation. We argue that just as species diversity is critical for the provision of multiple services, ecosystem stability and resilience (Mitchell et al., 2013), diversity of organizational type (a range of organizations) may be necessary for the stability and resilience of an industrial ecosystem. Using case study methodology to examine the newly emergent renewable energy sector in India, the paper provides evidence to support the framework and suggests that organizations exhibit four types of diversity in this ecosystem: (1) Diversity of function; (2) diversity of form; (3) diversity of interactions; and (4) diversity of knowledge. Moreover, each organizational type in the ecosystem varies in prominence over time as the ecosystem evolves. These findings have important implications for the adoption and establishment of new technologies and the management of technology life cycle.

INTRODUCTION

Rapidly rising demand for energy to meet economic growth targets and the objective of reducing import costs have led many developing countries like India to focus on new, renewable sources of energy such as solar, biomass and wind. Moreover, renewable energy holds great promise for inclusive development as over a third of the Indian population still lives in poverty (World Bank, 2014). However, providing energy access at the base of the pyramid requires building a renewable energy ecosystem that caters to this population. Ecosystem creation, an important function of innovation systems (Nelson, 1993; Lundvall, 2007), involves introducing new players and establishing linkages between new and existing ones to create new markets that did not previously exist. Diffusing new renewable energy technologies and generating livelihoods through ecosystem creation also promotes economic development, indicating that the management of new technologies is critical for developing economies.

Past research suggests that the emergence of new industrial sectors depends on nurturing capabilities in the industrial ecosystem and that the historical evolution of capabilities matters (Best, 2014; Nelson 1993, Porter 1990). Moreover, the environment shaping new and re-positioning firms is not external to the firms but an inter-institutional assemblage that enables the integration of capabilities (Best, 2014). Enterprises in an industrial ecosystem are agents within a complex adaptive system (Beinhocker, 2007; Garnsey, 1998; Iammarino, 2005). Further, just as diversity is critical for sustainability in biological ecosystems, enterprises with different capabilities are critical in an industrial ecosystem for the emergence and sustainability of new sectors.

While species diversity has been discussed in terms of technological capabilities (Best, 2014), other dimensions of diversity are neglected. In this paper we build on the literature on industrial and business ecosystems and focus on types of diversity required to nurture and foster emergent industrial sectors. Additionally, we extend the literature on national and regional innovation systems to suggest how emergent industrial sectors can foster diversity and generate new niches and markets that did not previously exist (Nelson, 1993, Lundvall, 2007).

This paper draws on theories of biological ecosystems to develop a conceptual framework for the establishment and evolution of ecosystems (Vihervaara et al., 2010). Species diversity is generally regarded as critical for ecosystem resilience (Mitchell et al., 2013); however, the introduction of invasive new species into the ecosystem can be detrimental to the survival of native species (Simberloff and Stiling, 1996). Additionally, species diversity helps resilience and contributes to the stability of the ecosystem as each species has a specific function and provides some services. Moreover, biodiversity is even more important for ecosystem multifunctionality, particularly if there is an appreciable lack of overlap between the groups of species that influence different ecosystem processes over time (Hector and Bagchi, 2007). The key research questions are: (1) What is the role and function of different participants in an emerging ecosystem for new renewable energy technologies? (2) How do these roles shift over time?

We apply these ideas to the emergent renewable energy sector in India and focus on solar, biofuels such as biogas from biomass and wind energy technologies. Viewing different types of organizations as different species in an industrial ecosystem, we suggest that each organizational type has a specific role and performs certain functions. Even if some species dominate the system by controlling key processes, or if other species provide similar services, species diversity might be necessary for other processes and to provide multiple services. For example, the creation of an ecosystem for renewable energy involves a range of organizations: the government, R&D laboratories, academic institutions, for-profit firms, international development agencies and non-governmental organizations (NGOs) among others. Each organizational type plays a role in the ecosystem and provides services that complement those provided by other types of organizations.

We use case study methodology to provide evidence from the Indian renewable energy ecosystem to support the conceptual framework developed in the paper. Data were drawn from interviews conducted in India over a 3-4 year period and this paper is part of a larger study on renewable energy in India and the U.S. Findings suggest four types of diversity in the ecosystem: (1) Diversity of function; (2) diversity of form; (3) diversity of interactions; and (4) diversity of knowledge. We also find that government and international agencies act as promoters, academic institutions and NGOs as trainers, and start-up entrepreneurial organizations as catalysts and disseminators. Also, the prominence of each organizational type in the ecosystem varies over time as the ecosystem evolves. These findings have important implications for the adoption and establishment of new technologies and the management of the technology life cycle.

The paper is organized as follows. The next section outlines the theoretical background that the paper draws upon for constructing the framework. Section three describes the context, data and methods. Section four describes the emergent framework. Section five outlines the findings from the study. Section six discusses the implications and conclusions.

THEORETICAL BACKGROUND

I draw upon the following three key theoretical lenses to examine the creation of an industrial ecosystem: (1) research on the composition of natural ecosystems; (2) industrial ecosystems (3) national innovation systems.

Ecosystems In The Natural Environment

Ecosystems are complex, adaptive systems characterized by historical dependency, non-linear dynamics, and multiple basins of attraction (Levin 1999). A key theme in the research on ecosystems in the natural environment is the idea of sustaining the system and maintaining resistance and resilience. Various researchers have suggested that species diversity in an ecosystem enables the provision of multiple services and contributes to resistance and resilience even if there is some redundancy in function across species. (Mitchell et al., 2013).

Various ecosystem services depend upon the movement of organisms and materials across landscapes and, therefore, are likely influenced by landscape connectivity – the degree to which a landscape facilitates the movement of organisms and matter. Connectivity also influences biodiversity and ecosystem function. Landscape composition and landscape configuration also affect the provision of ecosystem services (Mitchell et al., 2013). Chapin et al. (1996) indicate that an ecosystem is sustainable if key groups in the ecosystem maintain their characteristic diversity over the normal cycle of disturbance events. Sustainability is influenced by climate, soil resource supply, major functional groups of organisms, and disturbance regime that both influence and are affected by ecosystem processes. Moreover, oscillations in these factors must remain within stable bounds. Negative feedback is critical in constraining changes in these factors. For example, negative feedbacks associated with food availability and predation often constrain changes in the population size of a species. Linkages among ecosystems in a landscape can contribute to sustainability by creating or extending the feedback network beyond a single patch. Likewise, changing the composition of species can affect ecosystem processes and sustainability.

Palumbi, Mcleod and Grunbaum (2008) suggest that features of ecosystem stability—recovery, resistance, and reversibility—are features of overall resilience or robustness (Levin 1999, Levin and Lubchenco 2008), are measurable features of ecosystems, but cannot be studied in isolation and must be studied in the context of the ecosystem and its day-to-day function. Hence, they advocate studying ecosystem species and their interactions.

Elmqvist et al. (2003) indicate that ecosystem resilience may be critical for sustaining the the production of natural resources and ecosystem services in complex systems faced with uncer-tainty and surprise (Gunderson et al., 2002). Holling (1973, 1996) defines ecosystem resilience as the amount of disturbance a system can absorb and still remain within the same state or domain of attraction. Resilience also encompasses the ability of an ecosystem subject to disturbance and change to reorganize and renew itself. The definition includes the degree to which the system is capable of self-organization (versus a lack of organization, or organization forced by external factors), and how much it expresses a capacity for learning and adaptation (Carpenter et al. 2001). Biological diversity appears to play a substantial role in ecosystem resilience and in sustaining desirable ecosystem states in the face of change (Peterson et al. 1998). This role is related to the diversity of functional groups in a dynamic ecosystem undergoing change, and the species diversity within these groups (Walker 1995; Norberg et al. 2001). Luck et al. (2003) point to the importance of diversity in species and populations within functional groups in helping to maintain ecosystem services (i.e. ecological redundancy). Moreover, they suggest that variability in responses of species within functional groups to environmental change is critical to ecosystem resilience.

In ecosystems, species interact with other species directly and through abiotic factors in multiple ways, and, often form complex networks of interaction. (Olff et al., 2009) highlight other types of interactions besides predator-prey interactions that influence the distribution and abundance of organisms. For example, organisms interact with other species by producing resources and through other types of non-trophic interactions such as pollination or production of toxicants. Other types of interactions include spatial interactions (exchange of organisms, materials and energy), external environment forcing (e.g. when regional climatic conditions affect local air, water or soil temperature without receiving much feedback from it) and physical and chemical interactions that operate within ecosystems (Olff et al., 2009).

Industrial Ecosystems

Industrial ecosystems are analogous to biological ecosystems in that each process and network of processes is viewed as a dependent and interrelated part of a larger whole (Jelinksi et al.., 1992). Such systems need to be designed as many aspects of materials flows are defined by decisions taken very early in the design process (Jelinksi et al., 1992).

I follow Holland (1998) in viewing an industrial ecosystem as a complex adaptive system composed of subsystems at various levels and view firms rather than individuals as agents in the system. As noted above, research on ecosystems in the natural environment suggests that varied and frequent interactions between diverse, interconnected and autonomous agents are critical for ecosystem health. This includes maintaining resistance (the capacity to withstand external shocks without loss of function) and resilience (the capacity to recover from disturbance), generally dependent on maintaining species diversity (Ruhl, Kraft and Lant, 2007; Holland 1995; Allison and Hobbs, 2004). Diversity and interaction are, thus, necessary for resistance and resilience. Iansiti and Richards (2006) suggest that business ecosystem health is expressed via robustness, productivity and innovation (niche creation). Ecosystem boundaries are difficult to delimit perfectly as they are "open" systems. Moreover, ecosystem processes receive some energy and materials from outside and use energy to transform and recycle materials internally and build ecosystem structure and then move some energy and materials back to the outside (Ruhl et al., 2007). Also, as ecosystem processes operate at many scales, they can be studied at many scales.

For example, in the information technology (IT) ecosystem, the value of a single IT product is influenced by organizations dispersed across numerous traditional industries such as software application developers to venture capital firms (Iansiti and Richards, 2006). Applying complex systems ideas to technological transitions, MacCormack and Iansiti's (2004) study of Microsoft suggests that incumbent firms can respond effectively to technological transitions by paying attention to intellectual property development to address new market challenges. In developing a library of software components, the firm developed critical resources that enabled it to respond to major technological transitions.

Best (2014) describes the emergence of Boston's industrial ecosystem in terms of biological ecosystems. He notes that the population of small and medium-sized high technology enterprises offers a systemic form of opportunity creation and enacting processes for industrial innovation. These firms are embedded in a regional industrial ecosystem that facilitates on-going re-shuffling of the region's expertise, technology capabilities and financial resources not just for a single firm, but for the growth of a cluster of companies and that Boston's industrial ecosystem is a "manufactory of sectors".

Bustos et al. (2012) applies the concept of 'nestedness' in biological ecosystems to show that the geographical nestedness of industries holds at both national and global levels. Nestedness implies that ecosystems are composed of a core set of interactions to which the rest of the community is attached. Nested interaction networks also implies that specialist species interact mostly with generalist species and because the latter are less fluctuating, nestedness can enhance the survival of rare species, biodiversity and overall ecosystem stability and is thus an important structural property of interaction networks in ecology. Bustos et al. (2012) show that the nestedness of industry-location networks remains constant over time and that this empirical regularity can be used to predict the pattern of industrial appearances and disappearances over time.

National Innovation Systems

Research on industrial ecosystems also encompasses studies on networks and complex adaptive systems. These studies examine the growth of industrial sectors like biotechnology using alliance strategies to build networks (Powell, 1996) or as well as innovation systems at various levels – national, regional and technological. Moreover, the concept of resilience has also been used in research on economic development. Mäler (2008) suggests that, since wealth is an indicator of sustainable development, the value of changes in productive assets is an index of whether an economy is on a productive path or not. Hence, the resilience of an ecosystem (defined as the distance from the initial state to the threshold), an insurance against flips of the system into different basins of stability, can be regarded as a productive asset and should be regarded as a capital stock.

While these ideas have relevance for studying the emergence of new technological ecosystems, attempts to apply these concepts in the field of technology management are rare (some exceptions include M'Chirgui, 2005; Miyazaki and Islam, 2007; Silvestre and Dalcol, 2009). Although research on national innovation systems (Nelson, 1993; Lundvall, 2007) does conceive of national innovation systems as being comprised of various components, few explicit attempts have been made to model them in terms of ecosystems (Surie, 2013). Therefore, I use the concept of diversity in ecosystems, to examine how diversity in an emergent new technological ecosystem can contribute to resilience and adaptiveness. The next section discusses the context and methods.

CONTEXT AND METHODS

Context

The Indian economy is important player in the renewable energy sector (see Table 1). The focus of this paper is the biomass-based energy segment of the Indian renewable energy sector. Its selection is appropriate for the study as the sector is an emergent one as indicated by the presence of multiple technologies and variations of complementary systems suggesting that a dominant design has not yet emerged. Although solar and wind energy are the primary renewable energy sources to date as various missions were used to promote these sources, the government of India is also focused on a national bioenergy program and allocated INR 34 billion for the biomass mission, aiming to replicate the success of the National Solar Mission (REN21, 2014). According to Bloomberg New Energy Finance, investment in Indian clean-energy projects reached US $7.5 billion in the first three quarters of 2014, mostly fueled by the solar energy sector. Additionally, the US Export-Import Bank expects India to become its largest recipient of funding for clean-energy projects in 2015 (REN21, 2014).

Table1. Renewable Energy Country Attractiveness Index Scores and Rankings at September 2014 (Source: Ernst & Young, 2014).

				Technology-specific indices rankings							
Rank	Previous ranking	Country	RECAI score	Onshore wind	Offshore wind	Solar PV	Solar CSP	Biomass	Geothermal	Hydro	Marine
1	(2)	China	75.1	1	2	1	4	1	12	1	19
2	(1)	US	73.8	2	3	2	1	3	1	3	9
3	(3)	Germany	67.0	3	4	5	26	8	9	10	27
4	(4)	Japan	64.4	10	9	3	27*	2	3	4	12
5	(5)	Canada	60.3	4	11	7	24	12	19	5	4
6	(7)	India	60.2	8	19	4	3	15	13	7	11
7	(6)	UK	59.2	7	1	11	27*	5	18	26	1
8	(8)	France	58.5	12	8	8	17	10	15	16	5
9	(10)	Brazil	57.0	6	26	14	9	4	32	2	24
10	(9)	Australia	56.7	16	17	6	6	22	11	18	10
11	(11)	South Korea	55.4	21	13	10	25	11	28	17	3
12	(13)	Chile	54.3	25	24	9	2	20	10	14	14
13	(15)	Netherlands	54.2	11	6	21	27*	9	26	31	30
14	(14)	Belgium	52.8	20	5	19	27*	16	20	30	31*
15	(12)	Italy	52.5	22	20	15	11	14	6	11	22
16	(17)	South Africa	52.3	26	29	13	5	37	35*	21	18
17	(16)	Denmark	51.7	14	7	30	27*	13	35*	37	16
18	(18)	Portugal	50.8	23	21	23	18	24	16	20	7
19	(20)	Turkey	50.7	15	25	26	12	32	5	9	20
20	(21)	Thailand	50.5	31	39	12	20	17	29	34	28
21	(22)	Sweden	50.4	9	12	37	27*	7	24	12	13
22	(19)	Spain	50.2	28	23	18	10	26	34	29	15
23	(23)	Taiwan	49.4	30	16	17	23	29	21	23	26
24	(25)	Mexico	48.7	24	31	25	19	31	8	28	21
25	(24)	Austria	48.6	19	39	24	27*	18	22	15	31*
26	(26)	Peru	48.0	34	27	20	15	27	14	6	31*
27	(28)	Israel	46.6	39	37	16	8	38	35*	35	25
28	(29)	Morocco	46.4	27	35	28	7	39	35*	39	31*
29	(27)	Poland	46.3	18	18	36	27*	19	17	25	31*
30	(30)	Norway	45.5	13	14	38	27*	25	27	8	8
31	(32)	Ireland	45.3	5	15	40	27*	21	33	32	2
32	(31)	Romania	45.1	29	32	31	27*	34	25	27	31*
33	(33)	Greece	45.0	33	36	27	14	35	23	38	31*
34	(35)	Philippines	44.7	37	30	29	22	28	7	22	6
35	(34)	Saudi Arabia	44.6	35	38	22	13	40	30	40	31*
36	(37)	Kenya	44.3	32	34	32	16	30	4	24	29
37	(36)	Finland	44.2	17	10	39	27*	6	35*	33	31*
38	(40)	Russia	40.9	38	22	35	27*	36	31	19	23
39	(39)	Indonesia	40.9	40	33	33	21	23	2	13	17
40	(38)	Ukraine	40.4	36	28	34	27*	33	35*	36	31*

Biomass consumption for the provision of heat and electricity is increasing worldwide. Of the total biomass used for energy purposes, 60 per cent is traditional biomass which includes fuel wood, crop residues and dung, often gathered by hand and combusted in open fires or inefficient stoves for cooking, heat and lighting, while the remaining biomass is used for modern bioenergy. The latter includes a variety of biomass resources such as organic wastes, purpose-grown energy crops, algae which provide energy services including lighting, communication, heating, cooling and mobility. As solid, liquid or gaseous biomass can store energy for future use, it can be used to balance variable electricity generation form wind or solar systems when integrated into grids or mini-grids.

The bioenergy sector is complex due to the variety of feedstocks and technologies available for converting biomass to energy. The existence of data gaps and use of widely dispersed or non-commercial sources for biomass makes it challenging to track data and trends and difficult to measure production and demand (REN21, 2014). The bioenergy industry includes feedstock suppliers and processors, firms that deliver biomass to end-users; manufacturers and distributors of specialist biomass harvesting, handling and storage equipment and manufacturers of appliances and hardware designed to convert biomass to energy.

New regulations have been formulated to address rising concerns about sustainability, particularly in the United States and Europe, while industries have responded by adopting a number of initiatives by sector. In many developing countries, there are regulations focusing on the protection of biodiversity and impacts on poverty, land tenure, food security and social equity.

Modern biomass and off-grid installations of renewable energy technologies are aimed at rural communities which lack access to energy. Providing the means to cook, electricity for basic household chores and energy to engage in livelihood generation can boost economic growth and development (UNCTAD 2011) addressing socio-economic problems at the Bottom of the Pyramid (Prahalad, 2007). These technologies could also promote new sources of employment and increase prosperity in rural areas even through small, off-grid applications. Additionally, renewable energy technologies can be used to improve access to other services such as healthcare, promote greater access to information and communication technologies via the availability of electricity to power appliances and charge batteries, and promote gender parity by reducing the time spent on household chores so enabling women to take on additional income-generating activities. Rural enterprise development for renewable energy technologies can also reduce inequality and poverty.

Methods

I use case study methodology to examine the research questions regarding the diverse roles and function of various participants in an emerging ecosystem for new renewable energy technologies and how these roles shift over time.

Case study methodology is appropriate when asking how or why questions and when the phenomenon is rare, unique or critical for theory creation (Yin, 2003; Davis, Eisenhardt and Bingham, 2007). Following Lee (1999), I extend existing theory to develop new theory. Hence, I link the literature on biological ecosystems with that on industrial ecosystems and national innovation systems. Inductive case analysis is used to provide rich context and helps to understand different types of diversity in the renewable energy ecosystem and how these evolve in the context of emergence (Stevenson and Harmeling, 1990). Finally, the methodology reveals underlying processes by making concepts concrete (Eisenhardt and Graebner, 2007).

Cases were selected for elaboration of emergent theory as suggested by Eisenhardt and Graebner (2007) and include organizations in the traditional and modern biomass energy sector. I included different types of organizations to obtain rich detail and develop a robust theoretical framework by concretizing abstract ideas about diversity (Siggelkow, 2007). The case findings reported in this paper were drawn from interviews conducted as part of my Fulbright research study on the commercialization of renewable energy for base of the pyramid consumers (2013-2014; more than 50 interviews) while also drawing in general from a larger on-going study (involving more than 30 interviews from 2009-2011) of organizations focused on commercialization processes for emerging "green technologies" in India. Interviews were conducted in public and private sector organizations such as government officials, scientists, university researchers, CEOs of firms and non-governmental organizations (NGOs) serving Bottom of the Pyramid (BOP) consumers in the renewable energy sector (Yin, 1989). These data were supplemented by site visits, presentations, annual reports and other published material.

As noted earlier, the Indian context provides a favorable setting to study the emergence of organizational form in the context of creating an ecosystem for renewable energy for the population at the base of the pyramid. New policies on renewables were enacted with a focus on new energy technologies to alleviate poverty and facilitate social inclusion of the rural poor, a central element in renewable energy programs. For example, the National Policy on Biofuels (GOI, 2009) focuses on using non-food feed-stocks raised on degraded land for biofuel production. The government also availed of rural employment schemes to facilitate feedstock production and processing for the nascent biofuels sector (GOI, 2009).

Interviews were transcribed and the data were analyzed by using categorization and pattern-matching techniques as indicated by Yin (2003), Miles and Huberman (1994), Eisenhardt (1989). Drawing on my previous research on the emergence of organizational forms appropriate for the global expansion of firms in the biotechnology and software industries in India (Surie and Singh, 2013) and an application of this research to forms appropriate for the renewable energy sector (Surie, 2014), I began with the literature on biological ecosystems, industrial ecosystems and national innovation systems. I iterated from theory to data and vice versa to develop propositions and matched patterns obtained from the data with the above theories as recommended by Yin (2003). These analyses and propositions yielded a conceptual model for how diversity is a critical element in designing for resilience in when creating a ecosystem for renewable energy technologies. The conceptual framework is outlined in the next section.

FRAMEWORK: DESIGNING DIVERSITY IN ECOSYSTEMS FOR RESILIENCE AND RESISTANCE

Based on the literature outlined above which indicates the importance of diversity for the effective functioning and resilience of an ecosystem, I outline four types of diversity critical for ecosystems. These are described below.

Diversity of function

As species differ in the services they provide, diversity of function contributes to the productivity of the ecosystem (Midgley, 2012), particularly when services provided by different species are complementary. Maestre et al. (2012) analyzed the soils of 224 dryland ecosystems sampled from all continents except Antartica and assessed 14 functions in the carbon, nitrogen and phosphorus cycles in the soil. From this they evaluated how biodiversity (quantified as species richness of perennial vascular plants growing in these areas) relates to ecosystem multifunctionality across dryland ecosystems globally and confirm the biodiversity ecosystem function hypothesis. By analogy, we suggest that in industrial ecosystems, species diversity contributes to diversity of function and, hence should lead to greater productivity in the ecosystem as a whole (a mark of resilience according to Iansiti). For example, in an industrial ecosystem for renewable energy, producers of renewable energy technologies provide the services of technology to other companies that have the waste that needs to be processed. Consequently, each species performs a certain role in the ecosystem.

Diversity of form

Additionally, diversity in the form of species matters because species inhabit different environmental niches and require different levels of resources in the ecosystem. Li et.al (2004) provide evidence from both aquatic and terrestrial systems that smaller organisms claim larger shares of an ecosystem's productivity in relatively stable ecosystems. They suggest that several small organisms consume the same energy flux in a more balanced manner than does one large organism. This lowers the risk of under-exploitation or over-exploitation of the available resources and reduced the fluctuations of a community's biomass and nutrient cycling processes. Systems in which energy use is dominated by smaller organisms are expected to be more stable than ecosystems where large organisms consume considerable portions of a community's energy flux. Adapting this to industrial ecosystems, we suggest that the presence of organizations with multiple forms (including differences in size) is important to foster ecosystem stability.

Diversity of interactions

Interactions are critical for accessing, deploying and leveraging resources in complex ecosystems. Økland et. al (2009) suggest that the dynamics of species interaction is important in many fields of biology such as invasive biology where new interactions are frequent. Using bark beetles that colonize the same habitat (trees) as an example, they show that species in resource dependent systems may experience net interactions that fluctuate between negative and positive values over time. While increasing abundance of a competitor generally results in an inhibitory effect, they suggest that an increasing abundance of a second bark beetle species may be beneficial when it contributes to surpassing the threshold for colonizing living trees and, thereby, achieving a positive feedback by creating more habitat, but otherwise the effect is inhibitory through a combined exhaustion of the resource base.

Similarly, each organizational type may have a facilitating or inhibiting effect on other organizations in the ecosystem, depending on the resources and characteristics of the species.

Diversity of knowledge

Depending on its functions, form and interactions and by virtue of occupying a different position in the ecosystem, it therefore follows that each species has access to specialized knowledge that is emergent in the system. Moreover, the ability to leverage the specialized knowledge that emerges in the system contributes to success in facilitating interactions among species, provision of services, and overall ecosystem health.

DIVERSITY IN THE ECOSYSTEM FOR BIOMASS-BASED ENERGY IN INDIA

Evidence from the emergent ecosystem for biomas-based renewable energy suggests that the ecosystem has incorporated diversity as it has evolved. This ecosystem consists of different types of organizations, ranging from the government to non-governmental organizations and entrepreneurial start-ups, that vary in function, form, interactions and knowledge. These differerences are examined below.

Diversity of function

Organizations included in the ecosystem assume different functions and roles. For example, a key function of the government of India, through the Ministry of New and Renewable Energy, is to promote the generation and adoption of new technologies for biomass-based renewable energy. While resource mapping is required to assess the availability of biomass accurately, estimates suggest that approximatelly 550 million tonnes of crop residues are available, 70% of which is used as fodder. The remainder of 120-150 million tonnes has the potential to generate about 16,000 MW (megawatts), enough to power 3-4 cities like Delhi. The government's role is to conduct resource mapping, provide incentives to spur research and development in this field and uptake of the new energy by the state electricity boards, induce adoption of the best technologies, standardize technologies, ensure entry of entrepreneurial firms as well as established players. While the MNRE has been attempted to fulfil its role in each of these areas, despite the promise of biomass based energy, other competing renewable energy technologies have inhibited its adoption on a larger scale. In addition, the presence of so many types of biomass have led to a proliferation of technologies and there is, as yet, no commercially available dominant design or univeral digester that can handle various types of biomass. Finally, the MNRE must also ensure that biomass-based technologies are used in rural areas to promote economic and social inclusion.

The function of the universities and government laboratories and technical centers is different. It is to assist the government in its efforts to develop and deploy new biomass-based technologies by conducting research and development, generating new technologies for biomass, providing trarining and building skills and diffusing the technologies via licensing or spawning new ventures. For example, using grants from the government for pilot projects, professors at IIT-Delhi have developed expertise in biogas production from manure and diffused this technology in the state of Rajasthan. Additionally, scientists at other universities working on biomass digesters that handle various types of biomass, have, so far, created prototypes. The profusion of technologies makes the choice of a bio-digester difficult, compounded by the fact that different parts of the country have different types of biomass available.

Non-governmental organizations (NGOs) such as the Cow Shelter Group[1] are users of the technology and a test site for research laboratories. They deploy the technology in the field in rural areas and provide insights for modifications. They also help to encourage adoption by the rural population by creating the necessary infrastructure. For example, the Cow Shelter Group has a plant in its cow shelter to produce compressed natural gas from manure. Small scale versions of the technology have been introduced in farms where the number of cows is sufficient to generate biogas for cooking in rural homes.

---

[1] Names have been disguised for confidentiality.

Start-up ventures such as Renewable Power Systems (RPS) that have developed their own proprietary technology to provide turnkey services in biogas production play yet another role in the system. Besides testing technologies, creating infrastructure and providing new services, new ventures such as RPS also serve to spawn entrepreneurship.

Diversity of form

Each organizational type has an emergent form that has evolved out of its alliances and partnerships – heteromorphic form (H-form)– a form that consists of the simultaneous presence of multiple forms including hierarchy and alliances (described earlier in Surie and Singh, 2013; Surie, 2014). While heteromorphic form is a common pattern shared by members of the community, hierarchy emerges in the system as a whole as each organizational type occupies a different position or node in the network of alliances and partnerships. The size, scale and technology of these organizations also differs based on the function.

For example, MNRE works through central agencies, research and development laboratories, state governments and other nodal agencies and occupies a central position in the network as most projects are funded by the government and implemented according to the strategic vision of the government. Government research and development laboratories and other central agencies are extensions in the network for MNRE as they receive funding via grants from the government, but are hubs in their own right as they set technical standards for other organizations, both established firms and start-ups. NGOs form other nodes in the network; while some are more connected with the center than others, most NGOs doing work in rural areas form local hubs. For example, the Cow Shelter Group works with farmers and provides training on how produce biogas, look after cows, and also acts as a buyer, processor and seller of the milk produced in village farms. Likewise, start-up firms such as Renewable Power Systems (RPS) are more locally based but have access to the center. Renewable Power Systems is located in a major city and acts as a local hub for industrial and other organizations that want to turn their food and other biodegradable waste into energy. By piloting projects in various organizations, it showcases and diffuses its technology.

Diversity of interactions

The different types of organizations in the ecosystem also exhibit diversity of interactions both within the ecosystem and externally as they deal with different constituencies based on their purpose and vision. For example, MNRE interacts with other ministries and states to promote renewable energy through policies and incentives, selects the technologies to promote via government R&D organizations and interacts with other foreign agencies as well. Its interactions are at the macro level in the ecosystem. Government R&D labs and academic institutions interact with established and start –up firms and also with other foreign scientific institutions to learn about new technologies and with the government for obtaining grants. NGOs must look for funding from state and central governments and other international funding agencies such the Clinton Foundation, the World Bank, UNIDO and others, while at the same time, they interact with the beneficiaries of the technology in villages or urban slums. For example, Cow Shelter Group deals with other dairy farming organizations or cattle associations to obtain the best breed of cattle, but mainly deals with its farmer suppliers and customers in commercializing products such as fertilizer, milk, ghee (clarified butter) and cream. Lastly, start-up firms must deal with venture capital organizations, potential clients and research organizations to advance its technology and also with MNRE to ensure the support of the center for biomass-based technologies.

Diversity of knowledge

As a result of diversity in function, form and interaction, and by virtue of being at different positions in the network and facing different contexts in the ecosystem, each type of organization has a different knowledge base. For example, MNRE has expertise on how to direct and allocate resources to develop and diffuse new technologies, but lacks the abiity to commercialize technologies which is the main purview of start-up and established firms. Government academic institutions and R&D organizations produce prototypes at early stages of technology development and develop demonstration projects to be implemented at field sites and are, therefore, competent at setting standards at the early stages. For example, experimental techniques for biogas development from biomass at IIT-Delhi were implemented at the Cow Shelter Group which became self-sufficient in biogas production for its transportation needs. However, this is still a long way from commercialization. NGOs like the Cow Shelter Group (CSG) leverage these technologies to build trust and facilitate other ventures. By diffusing knowledge of how to manage cattle and produce biogas from manure (biomass), CSG was able to help villagers to improve conditions in the villages as they could generate clean fuel for cooking; this, in turn, enabled villagers to be more productive on the farms and facilitated commercialized dairy farming. Lastly, start-up firms like Renewable Power Systems that created linkages in an urban setting to turn food and other industrial waste into energy have technological expertise as well as knowledge of how to commercialize the technology and create new markets.

The cases reveal that as each type of organization interacts with others, a hierarchy emerges in the ecosystem as a whole. Each organizational type adds value in a specific way, contributing to the stability and sustainability of the ecosystem (Overholm, 2014). While entry of other organizations performing similar services may add redundancy, this is viable up to a point, depending on the resource availability or carrying capacity of the ecosystem (Økland et al., 2009). Moreover, stability also depends on keystone organizations (Iansiti and Levien, 2004) ensuring that they do not exercise dominance to the point where the existence of other organizations is prohibited (Li et al., 2004; Paine, 1966).

However, organizational function, form, interactions and knowledge may shift over time as the ecosystem evolves. For example, when a start-up firm like Renewable Power Systems becomes more established and markets stabilize, it may become the new center of the network rather than remaining a local hub. As adoption of the technology increases, the firm may be able to set standards for the technology, particularly if it becomes the dominant design. In contrast, MNRE may wind down subsidies, reduce incentives as they are no longer needed, and instead focus on developing technologies in other areas and forming new ecosystems. Similarly, academic institutions and R&D organizations may focus on improving the technology in incremental ways and optimizing performance. NGOs like The Cow Shelter Group may focus on new ventures and ways to commercialize biogas in other locations around India or assist other entrepreneurial ventures. These shifts would depend on the success of these organizations, the rate of adoption of the technology and the entry and growth of other supporting organizations.

DISCUSSION & CONCLUSION

The paper draws on the literature on ecosystems and sustainability in the natural environment and in industry to develop a framework for designing sustainable ecosystems. The framework suggests that industrial ecosystem resilience depends on the presence of diverse organizational types. I identify and elaborate on four dimensions of diversity emerging from the presence of different types of organizations that are relevant for ecosystem resilience: (1) diversity of function; (2) diversity of form; (3) diversity of interactions; and (3) diversity of knowledge. While these dimensions are distinct, they are also related and dependent on each other. For example, diversity of function is related to diversity of form in that the organization is designed to fulfill its purpose or function (Chandler, 1962).

The paper also applies the framework to the emerging renewable energy sector in India. As the case examples suggest, diverse organizations are involved in creating the ecosystem for renewable energy in rural areas. The case examples suggest that ecosystems must be designed to enhance diversity across the dimensions discussed in this paper to ensure ecosystem health and productivity. Each organizational type in the ecosystem adds value in different ways, and contributes to the emergence of hierarchy in the ecosystem, with some organizations at the center and others at the periphery. Linkages are built across organizations through interactions, contributing to exchange of knowledge and resources and embedding these organizations in the ecosystem.

Limitations

A limitation of this paper is that it focuses only on a four dimensions of diversity for ecosystem sustainability. There may be other dimensions of diversity that are not considered here. However, research on innovation in national systems and the competitive advantage of nations (Porter, 1990) and work on the acquisition of capabilities in emerging economies like Korea (Westphal, Kim and Dahlman, 1985) the diffusion of innovations (Rogers, 2003) supports the framework. Moreover, as this paper focuses on newly emergent ecosystems, additional dimensions may need to be considered when industrial ecosystems are mature or in decline.

In conclusion, this research has implications for theory and practice in developing economies where ecosystem creation is necessary for economic transformation. It can also yield insights for industrialized economies in areas where renewable energy can be used to revitalize the economy or to create ecosystems for new technologies. Future practice can be informed by these insights on how the four dimensions of diversity considered in this paper can contribute to ecosystem sustainability when designing an ecosystem. Future research could validate these dimensions by simulating ecosystem sustainability over time and through large sample empirical studies of ecosystems in other locations.acknowledgements

Acknowledgements should come before the references. .” Use the singular heading even if you have many acknowledgements. Avoid expressions such as “One of us (J.Q.A.) would like to thank ...”. Instead, write “J. Q. Author thanks ...”. Funding information may also be included here.

ACKNOWLEDGEMENTS

The author thanks the United States Department of State Bureau of Educational and Cultural Affairs for the Fulbright-Nehru Fellow award for field research in India during 2013-2014. She also thanks the anonymous reviewers of the International Association for the Management of Technology for their comments.

REFERENCES

Accessed December 26, 2014.

Beinhocker, E. (2007). The Origin Of Wealth: Evolution, Complexity, and the Radical Remaking of Economics, Random House, London.

Best, Michael H. (2014). Greater Boston's Industrial Ecosystem: A manufactory of sectors, Technovation, http: //dx.doi.org/10.1016/j.technovation.2014.04.004

Bustos, S., Gomez, C., Hausmann, R., Hidalgo, C.A. (2012). The dynamics of nestedness predicts the evolution of industrial ecosystems, PLOS ONE, Nov., Volume, 7, Issue11: e49393:1-8.

Carpenter, S. R., B. Walker, J. M. Anderies, and N. Abel. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems* 4:765-781.

Chandler, A.D. (1962). *Strategy and Structure : Chapters in the History of the American Industrial Enterprise*. Cambridge, MA: MIT Press

Chapin III, F. Stuart, Author(s): F. Stuart Chapin III, Margaret S. Torn and Masaki Tateno (1996). Principles of Ecosystem Sustainability, The American Naturalist, Vol. 148, No. 6 (Dec.): 1016-1037.

Davis, J.P., Eisenhardt, K.M., and Bingham, C.B. (2007). Developing theory through simulation methods, *Academy of Management Review*, 32, 2: 480-499.

Eisenhardt, K. M. & Graebner, M.E. 2007. Theory building from cases: opportunities and challenges. Academy of Management Journal, 50 (1): 25-32.

Eisenhardt, K. M. 1989. Building theories from case study research. Academy of Management Review, 14 (4): 532-550.

Elmqvist, Thomas, Folke, Carl, Nyström, Magnus, Peterson, Garry, Bengtsson, Jan, Walker, Brian and Norberg, Jon. (2003). Response Diversity, Ecosystem Change, and Resilience, Frontiers in Ecology and the Environment, Vol. 1, No. 9 (Nov.), pp. 488-494.

Garnsey, E. (1998). The genesis of the high technology milieu: a study in complexity, Int. J. Urben Reg. Res, 22 (3), 361-377.

Government of India (2009). National Policy on Biofuels, Ministry of New and Renewable Energy; http://pib.nic.in/newsite/erelease.aspx?relid=56469; http://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf (Accessed October 11, 2012).

Gunderson LH, Holling CS, Peterson GD. 2002. Surprises and sustainability: cycles of renewal in the Everglades. In Gunderson, L.H. and C.S. Holling, editors. Panarchy : understanding transformations in human and natural systems. Island Press, Washington, D.C., USA.

Hector, Andy, Bagchi, Robert (2007). Biodiversity and Ecosystem Multifunctionality, *Nature*, Vol 448:188-191.

Holland, J.H. (1998). *Emergence: From Chaos to Order*, New York: Basic Books.

Holling CS. 1973. Resilience and stability of ecological systems. Annu Rev Ecol Syst 4: 1-23.

Holling CS. 1996. Engineering resilience versus ecological resilience. In: Schulze PC (Ed). Engineering within ecological constraints. Washington DC: National Academy Press.

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCAQFjAA&url=http%3A%2F%2Fwww.ren21.net%2Fportals%2F0%2Fdocuments%2Fresources%2Fgsr%2F2014%2Fgsr2014_full%2520report_low%2520res.pdf&ei=UfCdVLfMJJCXyAS66IKYAw&usg=AFQjCNEAH94o0ejEoTUWdidfURm_bQQdkw

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCAQFjAA&url=http%3A%2F%2Functad.org%2Fen%2Fdocs%2Ftir2011_en.pdf&ei=DfCdVNKzMISSyQSovYKQAw&usg=AFQjCNFk7jHCTpYQ5zHyvg7TWsScDjYu2g

Iammarino, S. (2005). An evolutionary integrated view of regional systems of innovation: concepts, measures and historical perspectives, Eur. Plann. Stud. 13 (4), 497-519 (June).

Iansiti, M. and Richards, G.L., 2006. The information technology ecosystem: Structure, health and performance, The Antitrust Bulletin, 51 (1), 77-110.\

Iansiti, Marco and Levien, Roy (2004). Strategy as ecology, Harvard Business Review, March 2004: 1-10, Reprint R0403E.

Jelinski, L.W., Graedel, T.E., Laudise, R.A., McCall, D.W., and Patel, C.K.N. (1992). Industrial Ecology: Concepts and Approaches, *Proc. Natl., Acad., Sci., USA*, February, Vol. 89: 793-797.

Levin, S.A. (1999). Fragile Dominion: Complexity and the Commons, Reading, MA: Perseus Books.

Levin, S.A., Lubchenco, J. (2008). Resilience, Robustness, and Marine Ecosystem-based Management, BioScience 58: 27-32.

Li, Bai-Lian, Gorshkov, Victor G., and Makarieva, Anastassia (2004). Energy partitioning between different sized organisms and ecosystem stability, Ecology, 85 (7): 1811-1813.

Luck, G.W., Daily, G.C., and Ehrlich, P.R. 2003. Population diversity and ecosystem

Lundvall, Bengt-Ake (2007). National Innovation Systems – Analytical Concept and Development Tool, *Industry and Innovation*, Vol. 14, No. 1, 95-119.

M'Chirgui, Z., 2005, Smart card industry: A technological system, *Technovation*, 25:929-938.

MacCormack, A., Iansiti, M. (2004). Intellectual property, architecture, and the management of technological transitions: Evidence from Microsoft Corporation, Working paper.

Maestre, F.T., et al. (2012). Science 335, 214.

Mäler, K. (2008). Sustainable Development and Resilience in Ecosystems, Environ Resource Econ, 39: 17-24.

Midgley, Guy F. (2012). Biodiversity and Ecosystem Function, Science, Vol. 335: 174-175.

Miles, M.B. & Huberman, A. M. [1984] 1994. Qualitative data analysis. Newbury Park, CA: Sage Publications.

Mitchell, Matthew G.E., Bennett, Elena M., Gonzalez, Andrew (2013). Linking Landscape Connectivity and Ecosystem Service Provision: Current Knowledge and Research Gaps, Ecosystems, 16: 894-908.

Miyazaki, Kumiko; Islam, Nazrul (2007). Nanotechnology systems of innovation – An Analysis of industry and academia research activities, Technovation, 27: 661-675.

Nelson, R. R. (1993). *National Innovation Systems*, NY: Oxford University Press.

Norberg, Jon, Dennis P. Swaney, Jonathan Dushoff, Juan Lin, Renato Casagrandi, Simon A. Levin (2001). Phenotypic Diversity and Ecosystem Functioning in Changing Environments: A Theoretical

Framework, Proceedings of the National Academy of Sciences of the United States of America, Vol. 98, No. 20, pp. 11376-11381.

Økland Bjørn, Skarpaas, Olav, Kausrud, Kyrre (2009). Threshold facilitations of interacting species, Population Ecology, 51: 513-523.

Olff, H. , Alonso, D., Berg, M.P., Eriksson, B. K., Loreau, M., Piersma, T., and Rooney, N. (2009). Parallel Ecological Networks in Ecosystems, Philosophical Transacctions: Biological Sciences, Vol. 364, No. 1524, Food-Web Assembly and Collapse: Mathematical Models and Implications for Conservation (Jun., 27), pp. 1755-1779.

Overholm, Harald (2014). Collectively created opportunities in emerging ecosystems: The case of solar service ventures, Technovation, http://dx.doi.org/10.1016/j.technovation.2014.01.008.

Paine, Robert T. (1966). Food Web Complexity and Species Diversity, The American Naturalist, Vol. 100, NO. 910, Jan-Feb, 65-75.

Palumbi, Stephen R., McLeod, Karen L., Graünbaum, Daniel (2014). Ecosystems in Action: Lessons from Marine Ecology about Recovery, Resistance, and Reversibility, Bioscience, Vol. 58, No. 1: 33-42.

Peterson G, Allen CIR, Holling CS. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1:6-18.

Porter, M. E. (1990).*The Competitive Advantage of Nations*. New York: Free Press. (Republished with a new introduction, 1998.)

Powell, W. W., K. W. Koput, and L. Smith-Doerr. 1996. "Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology." *Administrative Science Quarterly* 41:116-145.

Prahalad, C. (2007). *The Fortune at the Bottom of the Pyramid: Eradicating Poverty Through Profits*, Pearson Educational/Wharton School Publishing, Upper Saddle River, N.J.

REN21 (2014). Renewables 2014: Global Status Report, Renewable Energy Policy Network for the 21st Century.

Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). New York: Free Press.

Ruhl, J.B., Kraft, Steve E., Lant, Chirstopher L. (2007). The law and policy of ecosystem services, Washington D.C., Island Press, pp. 13-35.

services. *Trends in Ecology and Evolution* 18 (7): 331-36.

Siggelkow, N. 2007. Persuasion with case studies. Academy of Management Journal, 50 (1): 20-24.

Silvestre, B. and Dalcol, P.R.T. (2009). Geographical proximity and innovation: Evidences from the Campos Basin oil and gas industrial agglomeration – Brazil, *Technovation*, 29: 546-561.

Simberloff, Daniel, Stiling, Peter (1996). How risky is biological control? *Ecology*; Oct 1996; 77,7:1965-1974.

Stevenson, Howard and Harmeling, Susan (1990). Entrepreneurial Management's Need for a More "Chaotic" Theory, *Journal of Business Venturing*, 5: 1-14.

Surie, G. (2013). Innovating via emergent technology and distributed organization: A case of biofuel production in India, Technological Forecasting & Social Change 80 (2013) 253–266.

Surie, G. (2014). Ecosystem Creation and Organizational Form: Insights from Renewable Energy in Rural India, Proceedings of the IAMOT Conference, 2014, Washington, D.C. U.S.A.

Surie, G. and Singh, H. (2013). A Theory of the Emergence of Organizational Form: The Dynamics of Cross-border Knowledge Production by Indian Firms, *E:CO* Issue Vol. 15 No. 4, pp. 37-75.

UNCTAD (2011). Technology and Innovation Report, 2011: Powering Development with Renewable Energy Technologies. Accessed December 26, 2014.

Vihervaara, Petteri, Ro¨nka, Mia, Walls, Mari (2010). Trends in Ecosystem Service Research: Early Steps and Current Drivers, *AMBIO*, 39:314–324.

Walker, Brian (1995). Conserving Biological Diversity through Ecosystem Resilience, Conservation Biology, Vol. 9, No. 4, pp. 747-752.

Westphal, Larry E., Linsu Kim and Carl J. Dahlman (1985), 'Reflections on the Republic of Korea's acquisition of technological capability', in Nathan Rosenberg and Claudio Frischtak (eds), *International Technology Transfer: Concepts, Measures and Comparisons*, New York: Praeger.

Yin, R. K. ([1989, 1994] 2003). *Case study research: Design and methods*. Newbury Park, CA: Sage Publications.