ADDRESSING SUSTAINABILITY THROUGH RENEWABLE ENERGY ECOSYSTEMS IN INDIA

ABSTRACT

1. Purpose of the paper

This paper focuses on promoting the sustainability of renewable energy ecosystems, to ensure socio-economic development in the present without compromising future needs (Brundtland Report, 1980). The topic is critical for emerging economies where exacerbating demand for environmental resources is likely to deplete resources rapidly and for managing waste to prevent environmental damage.

2. Related work

Achieving sustainable development requires decoupling economic growth from natural resource use (United Nations, 2017). The UN's (2015) Sustainable Development Goals (SDGs) include providing affordable clean energy, promoting sustainable consumption and production, conserving terrestrial ecosystems and ensuring work and growth. However, globally, 1.06 billion people have no electricity and 3 billion people lack clean fuel for cooking (United Nations, 2017).

Global trends indicate that total domestic material consumption rose from 48.7 billion tons to 71.0 billion tons over 2000-2010 due to increased use of natural resources worldwide. Moreover, land productivity decline and biodiversity loss continue and target GDP growth rates in developed and developing countries were missed from 2010-2015 (United Nations, 2017).

The paper focuses on renewable energy for rural populations in developing countries for two reasons: (1) access to energy is a major problem; and, (2) using renewable energy can reduce the burden on the environment. However, ensuring environmental sustainability through renewable energy ecosystems requires establishing their economic viability.

Drawing on sustainability, industrial ecosystems (Iansiti and Richards, 2006) and complexity research (Holland, 1998; 1995), the paper views industrial innovation systems as ecosystems with companies occupying different hierarchical trophic levels as in a food web and materials and energy forming metabolic linkages among them (Ashton, 2009; Graedel, 1996; Hardy and Graedel, 2002; Jelinski et al 1992). Such industrial ecosystems are organized around product/material supply chains or in defined geographies (Ashton, 2009; Boons and Baas, 1997). Interfirm linkages include shared management of common utilities, infrastructure (e.g. energy, water), common services with resource conservation benefits, and by-product reuse (Chertow et al., 2008).

3/4. Design/Methodology/Approach and Findings

Case study methods (Yin, 2003) are used to study the renewable energy sector in India. A conceptual framework is presented to suggest how rural renewable energy ecosystems can promote environmental and socio-economic sustainability. Case data support the framework. Findings indicate that the ecosystem must be designed to generate various types of resources and achieve scale through interactions among diverse players to ensure sustainability.

5. Research limitations/implications

This paper extends past research on industrial ecosystems and also links it with the literature on sustainability. Additionally, it addresses how to establish renewable energy ecosystems, an under-researched and important area. Limited data could be overcome through future large sample studies.

6. Practical implications

This research can help government policy makers and businesses attempting to establish new sustainable innovation ecosystems in both developing and industrialized countries.

7. Originality/value of the paper

The paper is original and valuable because it: (1) addresses a topic of critical importance in the 21st century; (2) finds that stimulating innovation and generating livelihoods to scale the industrial ecosystem is critical for achieving environmental and socio-economic sustainability.

Keywords: *sustainability, renewable energy, industrial ecosystems, innovation, India*

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1. INTRODUCTION

It is increasingly accepted that it is imperative to take the natural environment into account and eschew reliance on excessive and non-sustainable exploitation of natural resources such as fossil fuels to ensure the health of our planet and resources for future generations (Heal, 2010; Arrow et al., 2010). Moreover, researchers and policy makers have suggested that economic growth should be decoupled from natural resource use to achieve sustainable development (United Nations, 2017). However, while solutions such as using clean energy from renewable sources have been advocated to reduce the carbon footprint (Scheel, 2016), these require a transition to new technologies and new business models and corresponding behavioral and social change to displace currently entrenched carbon-based systems (Surie, 2017).

Over the past decade, the realization that reliance on renewable energy could reduce imports of petroleum, improve self-reliance from an energy stand-point, reduce environmental degradation and also yield the promise of potentially becoming a global leader of a new renewable energy sector by developing capabilities has led emerging economies such as China, India and Brazil to increase investments in renewable energy (REN21, 2017). Moreover, renewable energy use is particularly relevant in emerging economies as their rise has fueled increases in the per capita consumption of electricity and other resources. Finally, the potential of transforming waste and residues into energy and upcycled products through innovation to increase the bottom line is appealing (Scheel, 2016; MITSloan & BCG, 2013; McDonough and Braungart, 2010).

The UN's (2015) Sustainable Development Goals (SDGs) include providing affordable clean energy, promoting sustainable consumption and production, conserving terrestrial ecosystems and ensuring work and growth. However, globally, 1.06 billion people have no electricity and 3 billion people lack clean fuel for cooking (United Nations, 2017). Moreover, global trends indicate that total domestic material consumption rose from 48.7 billion tons to 71.0 billion tons over 2000-2010 due to increased use of natural resources worldwide. Additionally, land productivity decline and biodiversity loss continue and target GDP growth rates in developed and developing countries were missed from 2010-2015 (United Nations, 2017).

This paper focuses on renewable energy in India where, despite progress in the past decade, 20% of the population remains poor and have little access to basic services such as electricity (61%), toilets (21%) and tap water (6%) in 2016 (World Bank, 2016). Increasing access to energy by promoting the adoption of renewable energy is a major opportunity to reduce the burden on the environment. However, ensuring environmental sustainability through renewable energy ecosystems requires establishing their economic viability. Specifically, this paper focuses on solar energy, a leading renewable sector in India targeted by the Government of India to grow to 100 GW of solar power by 2022 (Yenneti, 2016).

Consequently, the paper draws on research on sustainability (Arrow et al., 2010; Heal, 2011) and natural ecosystems (Ashton, 2009; Graedel, 1996; Hardy and Graedel, 2002) to inform the design of industrial ecosystems (Iansiti and Richards, 2006) to provide renewable energy in a manner that is environmentally and socio-economically sustainable (McDonough and Braungart, 2010; McDonough and Braungart, 2002). The paper views industrial innovation systems as ecosystems with companies occupying different hierarchical trophic levels as in a food web and materials and energy forming metabolic linkages among them (Ashton , 2009). Industrial ecosystems are organized around product/material supply chains or in defined geographies (Ashton, 2009; Boons and Baas, 1997). Interfirm linkages include shared management of common utilities, infrastructure (e.g. energy, water), common services with resource conservation benefits, and by-product reuse (Chertow et al., 2008). Moreover, sustainable wealth can potentially be created by modifying the conventional growth paradigm and relying on technology and innovation to create businesses that regenerate regional national resources and are simultaneously economically competitive and socially beneficial (Scheel, 2009).

The paper examines the following research question: How can renewable energy systems promote environmental and socio-economic sustainability? A conceptual framework is presented to suggest how renewable energy ecosystems can promote environmental and socio-economic sustainability. Case study methods (Yin, 2003) are used to study the renewable energy sector in India. Case data support the framework. Findings indicate that the ecosystem must be designed to generate various types of resources and achieve scale through interactions among diverse players to ensure sustainability.

2. PAST RESEARCH

2.1. Sustainability

The concept of sustainability dates back to Malthus and was addressed extensively in the 1970s literature on exhaustible resources (Heal, 2011). The Brundtland report (1987) defined sustainable development as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). Thus, sustainable development is economic development that lasts (Pearce and Atkinson, 1993b), narrowly defined as real Gross Domestic Product per capita or broadened to include indicators of development such as education, health, "quality of life" including human freedom (e.g. the United Nations Development Programme's Human Development Index (HDI); (UNDP, 1992)). It is continuously rising, or non-declining consumption per capita or whatever indicator is used to measure development (Pearce and Atkinson, 1993b). It emphasizes human wellbeing (Arrow et al., 2010; Heal, 2011; Pierce and Atkinson, 1993) and deals with the question of how well off people are now and how this level changes over time and whether current levels of wellbeing can be sustained over time (Heal, 2011; Pearce and Atkinson, 1993b). Although measuring sustainability is difficult, Pearce and Atkinson's (1993a) first proposed a measure of sustainability that examined what a generation was leaving in terms of capital assets to later generations (Maler, 2007). Pearce and Atkinson (1993a; 1993b) argued that if natural wealth declined over time, no economy meets the conditions for strong sustainability which requires conservation of all exhaustible and renewable resources and does not accept substitutability among different assets. However weak sustainability merely requires that the overall stock of capital must not decline. Weak sustainability can be met if the depreciation of natural capital, also referred to as total resource rents (arising when a natural asset is run down) are invested in man-made capital so that the constant capital rule is satisfied (Pearce and Atkinson, 1993b). As manmade capital also depreciates, further investments must be made to offset this loss. The "constant capital" rule is known as weak sustainability which assumes that forms of capital are completely interchangeable. They apply the rule to 22 countries and find that eight countries are unsustainable, even on a weak sustainability rule. While "overuse" of their respective natural resources is well-documented for these countries (where overuse refers to a rate of depletion over and above the ability to invest in alternative assets), justifications for this development path are not consistent with intergenerational equity and sustainable development.

More recently, Heal (2011) notes that we are leaving built capital (e.g. freeways, airports, buildings and infrastructure) and intellectual capital (e.g. research and development programs have developed cures for diseases, new products and new ways of doing things) for future generations. However, the question remains as to whether human labor and ingenuity can adequately compensate for a depleted natural environment and whether we can continue to trade natural environments and endangered species for better technology and infrastructure. Massive expansion of fossil fuel use, loss of species, clearing of forests, depletion of populations of large fish in the oceans suggest that we are depleting our natural capital faster than ever before and that old tradeoffs may not continue to work. All aspects of natural capital cannot be replaced by physical, financial or intellectual capital (Heal, 2011). For example, forests and coral reefs and ecosystems in general cannot be fully replaced, so sustainability requires that we maintain some of our natural capital intact as it provides services that we cannot replace. While valuing physical capital is relatively easy, intellectual capital is harder to value though there are some measures such as the value of patents, there are no markets or prices for some types of natural capital such as biodiversity making it very difficult to value. Heal (2011) suggests calculating shadow prices to value such natural assets. If these natural assets become very scarce the shadow price will rise sharply. Therefore, Heal (2011) argues that constancy of the value of total capital could mask a decline in important types of natural capital essential to our continuing wellbeing as billions of dollars of built or intellectual capital may be needed to compensate for the loss of one unit of scarce natural capital. Finally, Heal (2011) suggests that a widely used measure of sustainability is Adjusted Net Savings (a measure of the total change in the value of all of a nation's capital stocks - physical, intellectual and natural) developed by the World Bank (World Bank 2006 and 2010; Hamilton and Hartwick, 2005). If Adjusted Net Savings is positive, the country is sustainable, if it is negative, it is not (in the sense of weak sustainability).

2.2. Industrial ecosystems, complexity and sustainability

Industrial ecosystems have been considered as complex adaptive self-organizing systems to which ecological models have been applied (Hardy and Graedel, 2002; Ashton, 2009). Complexity is characteristic of a wide variety of systems and has been used to study biological systems, cardiovascular systems, economies, human societies, neural systems, stock markets and weather systems. Likewise, both natural and industrial ecosystems are complex systems. Complex adaptive systems are self-organizing and non-linear; outcomes arise from the action of agents at a lower level of aggregation; agents co-evolve with one another and simple rules constrain behavior such that simple building blocks can give rise to complex behavior (Holland and Miller, 1991). Complex adaptive systems evolve over time through the entry, exit, and transformation of agents. Continuous evolution ensures that CASs operate far from the equilibrium of what may otherwise be thought of as globally optimal system performance (Holland and Miller, 1991; Kauffman, 1993). Complexity literature (Holland, 1998; Holland, 1995; Surie and Hazy, 2006) emphasizes that complex adaptive systems function at an optimum or the "edge of chaos" when interactions among agents within the system need to remain within a delicate range to prevent stagnation and decay on the one hand , and unpredictable random dynamics on the other (Kauffman, 1993). Complex systems also exhibit emergent properties that cannot be deduced from the properties of the participants or the rules (Goldstein et al., 2010). Additionally, they develop by co-evolving with the environment and other systems and once a system has progressed a way along its "possibility tree" it may exhibit path dependence (Smith, 2002).

Concepts from ecology and ecosystems in the natural environment (Odum, 1969) have been applied to Industrial ecosystems (Zhu and Ruth, 2013; Iansiti and Richards, 2006; Graedel, 1996) which are regional, sectoral, or network-based industrial systems comprised of producers, consumers and regulatory agencies that exchange materials, energy and information with each other and the environment (Zhu and Ruth, 2013). Additionally, the concept of symbiosis in biology (Odum, 1969) has been applied to industrial ecosystems that are connected networks of interacting agents. Ruth (2009) suggests that sustainable industrial ecosystems avoid the unintended consequences of production and consumption processes. Additionally, such industrial ecosystems provide a more integrated and closed-loop approach to industrial production and consumption as they incorporate recycling, use of by-products and life cycle considerations. Thus, industrial ecosystems encompass not only economic prosperity but also the mitigation of material and energy throughput and environmental impacts (Zhu and Ruth, 2013). Moreover, an industrial ecosystem can develop with intentional, strategic and institutional pursuit of environmental goals (Baas and Boons, 2004; Chertow and Ehrenfeld, 2012). Among key concepts drawn from biological ecosystems and applied to industrial ecosystems is the importance of species diversity in maintaining resilience, the ability to recover from shocks, as different species perform different functions and provide different services in the ecosystem and their interactions promote resource flows in increasingly complex networks as the system matures (Odum, 1969).

Eco-efficiency is an important standard for ecosystems to be technologically feasible and economically attractive and can be achieved by reducing material and energy throughput and by optimizing current production. However, focusing on a single target such as eco-efficiency may not be helpful to ensure the resilience of an industrial ecosystem – its ability to endure in a fluctuating market environment. The concept of resilience has been applied to ecosystem sustainability and has been used to provide guidelines for design and management of supply chains (Pettit et al., 2010). Based on Holling (1973), resilience is defined as the ability of a system to absorb changes and still persist, while stability is the ability of a system to return to an equilibrium state. Resilience refers to the ability of the system to retain essentially the same function, structure, identity and feedbacks" and is a dynamic concept (Walker et al., 2004) thus indicating that the system stays in the same "basin of attraction" (Zhu and Ruth, 2013). The state variables that describe a system constitute the state space of the system; a basin of attraction is a region in the state space where the system tends to remain and move about or toward equilibrium (i.e. an attractor, in the basin). When a system has more than one basin of attraction, these basins and their boundaries form a stability landscape for the system which is subject to change due to exogenous factors at higher or lower scales (e.g. changes in institutions or individual preferences). Adaptability is the collective capacity of human actors in the system to manage resilience (Walker et al., 2004). Resilience has been invoked in the supply chain literature in connection with the severity of supply chain disruptions and complements research on risk in supply chains (Craighead et al., 2007). Though supply chains are more narrowly conceived than industrial supply chains, the former can shed light on the discussion of an industrial ecosystem's resilience including the trade-off between risk and flexibility (Zhu and Ruth, 2013). Likewise, achieving sustainability in the industrial ecosystem can increase the complexity of supply chains as it requires closing the material loops through recycling, design of products and processes, regulation and integration of activities. Zhu and Ruth's (2013) simulations indicate that although industrial ecosystems are more resilient with more firms and exchanges, they may also be vulnerable to unforeseen disruptions, especially when disruptions are initiated in highly connected firms. Increased diversity represents an increase in the number of firms and exchanges, which makes an industrial ecosystem less resistant at the firm level because of the propagation of disruptions; however, it is less vulnerable at the system level and overall resilience increases as long as the dependency level is low. Resistance only increases if diversity brings with it redundancy of firms and exchanges and thereby reduces inter-firm dependency. Thus, along with industrial symbiosis and inter-firm resource sharing (Chertow, 2007), it should be noted that better management of inter-firm exchanges can help to maintain industrial ecosystem resilience (Zhu and Ruth, 2013). Chertow's (2007) examination of industrial development in 15 projects where symbiosis or inter-firm exchanges were intentionally planned versus 12 projects where symbiosis emerged in a self-organized fashion indicates that using industrial symbiosis to alleviate environmental degradation has a greater chance of success when early-stage precursors of symbiosis are nurtured (Chertow, 2007).

Although McDonough and Baumgart (2002) and others (Scheel, 2016) have argued for the need to go beyond sustainability and create sustainable wealth by moving towards circular value ecosystems and using technology and innovation to transform residues into valuable resources to reduce environmental impact and benefit the community, research on this topic is still nascent. Additionally, further research is required to understand and overcome the challenges of transitioning from the conventional paradigm of economic growth to a system that fully incorporates the impact of activities on the environment.

2.3. Sustainability in Renewable Energy Ecosystems

A major benefit of renewable energy is the reduction of greenhouse gas emissions, environmental impact and use of fossil fuels (Pierie et al., 2016). Although renewable resources are often seen as sustainable resources, this is not always the case as renewable refers to the energy resource and not to the processes associated with the extraction and refining of the resource (Pierie et al., 2016). In many instances, extracting energy from a renewable resource still requires fossil input which will have an impact on the environment and, therefore, on sustainability. Other factors that influence the environmental sustainability of a renewable resource include materials and production processes used and the energy system in which it is integrated. While sustainability is a complex concept and measures include economic and social indicators, Pierie et al. (2016) note that measures should include the efficiency, carbon footprint and environmental impacts of renewable resources to enable better planning and decision-making towards achieving a more sustainable energy system. Techniques such as Life Cycle Analysis (LCA) and energy analysis have been used to measure sustainability. For example in the context of biogas, the focus has been on feedstocks and biogas production pathways, transport distances, the biogas production process itself and different end uses of biogas. Energy analysis studies quantify all the energy and material inputs and outputs in a product's life cycle. Results are given in a wide range of impact categories (i.e. climate change, ozone depletion, agricultural and land occupation, etc.) adding up to more than 20 indicators. Problems with LCA include the large amount of data required and availability of data and the resource and time intensities of LCA. Focus on specific biogas technologies and end uses as well as the variety and scope of indicators makes comparison and interpretation of results difficult. Pierie et al. (2016) use systems analysis to propose an approach to measuring environmental sustainability using a modular approach for the green gas production pathway which is defined as a collective of physical processes working together to achieve a common goal (e.g. biogas production). These production pathways are comprised of a number of sub-modules. Their model incorporates temporal dynamics which can influence sustainability. Three environmental indicators that correlate with the definition of "strong sustainability" are used: (Process) Energy Return on Investment (PERIO), the carbon footprint indicated by Global Warming Potential 100-year scale (GWP100), and environmental impact by the ReCiPe 2008 Eco indicator which is an overall expression of the total load on the environment (human health, ecosystems and resource depletion). The three unites are expressed per Gigajoule of energy produced (Pierie et al., 2016).

Similarly, Liu (2014) proposed a general sustainability indicator or index to reflect all aspects of sustainability of a renewable energy system, as well as the interaction of its subsystems and or components. Liu (2014) suggests that the measure should reflect the concept of sustainability, measure quality corresponding to sustainability goals, be based on timely and reliable information, reflect a strategic view and take into account system optimization and longevity of system design. Liu (2014) builds a model using a hierarchical process and including environmental (e.g. emissions, proportion of different renewable energies in a system, energy efficiency), economic (e.g. costs, return on investment, payback) and social considerations (e.g. job creation, benefits to residents).

Terrapon-Pfaff et al. (2014) note that small-scale and community-based renewable energy projects are important forms of development assistance for reaching the energy poor in developing countries. They examine 23 local development projects supporting renewable energy technologies including solar, wind, hydro and biomass power used for food preparation, lighting, electrification or irrigation in over 17 different developing countries in Sub-Saharan Africa, Latin America, Asia and the Middle East. They found that access to sustainable and affordable energy services is crucial for reducing poverty in developing countries and small-scale projects did improve access to energy. Even though only five interview partners were able to quantify the increase, these five projects alone provided 350 additional persons with clean electricity, lighting, heating or cooking solutions with up to 2500 additional people gaining access through on-going scaling activities. However, the number of people using the energy to start business activities was small with irrigation projects being the exception. While jobs established during the implementation process still existed, additional employment opportunities were limited. Moreover, renewable energy use reduced deforestation through reduced use of firewood, preserved diversity, prevented unsustainable land-use changes and reduced smoke and GHG emissions by replacing wood and fossil fuels as the energy source. Positive environmental effects were quantified (estimated) for the initial project; while quantifiable results were not obtained for the post-project period, most of the technological devices introduced in the project were still operating suggesting that the projects were successful in reducing CO_2 emissions and fire wood and fossil fuel use on an ongoing basis. Overall, the majority (78%) of projects continued to operate and were in use by beneficiaries, 48% were fully functioning and 30% were largely operational, while 13% were operating to a limited extent and 9% failed. Key factors for success were the effective functioning of the technical system, financial viability of the service, effective management of the project and external factors such as institutional and policy developments or environmental conditions (Terrapon-Pfaff et al., 2014).

Other papers on renewable energy and sustainability focus on experiments to optimize or model individual renewable energy technologies for specific purposes (Castillo-Téllez et al., 2017; Santos-González et al., 2017). However, insufficient efforts have been made to link the literature on sustainability with that on industrial ecosystems and the research on renewable energy in developing economies despite the overwhelming need for energy and importance of establishing industrial ecosystems to ensure both environmental and socio-economic sustainability.

Despite their desirability, implementation of solar energy projects has faced regulatory and financing hurdles in addition to the difficulties of educating the public and diffusing technologies in emerging economy markets like India (Umamaheswaran and Seth, 2015). Nevertheless, the government has encouraged them because of the promise of lower cost energy to replace petroleum imports via new policies that facilitate research in this area, attract entrepreneurs and large established companies (Surie, 2017). In addition, efforts have been made to increase outreach to outlying areas where there is either no grid connectivity or no electricity despite availability of the grid. Investments have increased and the cost of solar photovoltaics (PV) has become increasingly competitive with traditional power sources (REN21, 2017).

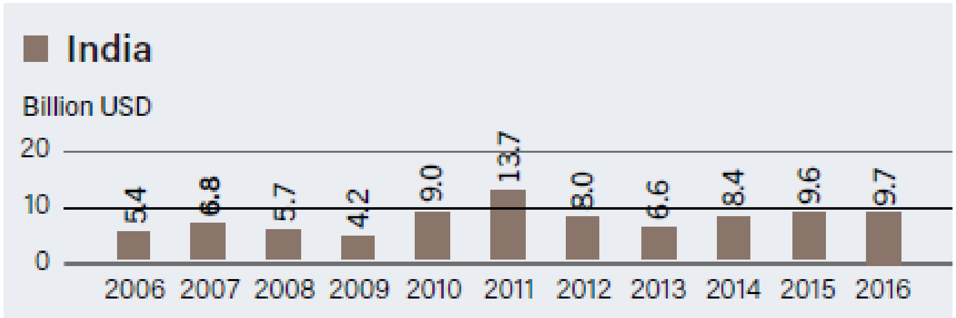
3. CONTEXT AND METHODS

3.1. Context

India is an important player in the renewable energy sector. This paper focuses on solar energy segment of the Indian renewable energy sector selected because of its potential to provide clean power on a large-scale and also address rural areas that are off the grid. Additionally 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. 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. The levelized cost of electricity from solar PV dropped to almost a quarter of what it was in 2009, and is estimated to drop another 66% by 2040 and by 2021, it will be cheaper than coal in China, India, Mexico, the U.K. and Brazil as well (Bloomberg New Energy Finance, 2017).

Renewable energy continued its development in 2016 against the backdrop of comparatively low fossil fuel prices and dramatic price declines of several renewable energy technologies and continued attention to energy storage. Global energy-related carbon dioxide emissions from fossil fuels and industry were nearly flat in 2016 due to declining use of coal worldwide and also to improvements in energy efficiency and greater use of renewable energy. Renewable energy provided an estimated 19.3% of global final energy consumption as of 2015. The power sector experienced the greatest increases in renewable energy capacity in 2016 whereas growth of renewables in the heating and cooling and transportation sectors was lower. In 2016 renewable energy spread to a growing number of developing and emerging economies and the sector employed 9.8 million people, an increase of 1.1% over 2015. Asia, led by China, accounted for 62% of all renewable energy jobs (not including hydropower). While community renewable projects continued, the pace of growth slowed and such projects have begun to expand into energy retailing (supply), storage and demand-side management. An estimated total of 161 GW of renewable power capacity was added in 2016, the largest annual increase ever with total global capacity up nearly 9% over 2015 and accounted for an estimated nearly 62% of net additions to global power generating capacity. Solar PV accounted for more additional capacity (net of decommissioning) than did any other power generating technology and represented 47% of newly installed power capacity in 2016 with most of the remainder contributed by wind (34%) and hydropower (15.5%). Ongoing growth and expansion of renewable power capacity was driven by the decline in prices for renewable energy prices, rising power demand and targeted renewable energy support mechanisms. At least 17 countries had enough solar PV capacity to meet 2% of their electricity demand and several countries met far higher shares in 2016 (REN21, 2017). In concentrating solar thermal power, all new facilities incorporated thermal energy storage. Globalization of solar thermal heating and cooling technologies continued and the use of solar thermal technologies expanded in India and Mexico, particularly in non-residential segments (REN21, 2017). India was the third largest market and ranked fourth globally for additions and seventh for total capacity. India added about 4.1 GW (up from 2 GW in 2015); Tamil Nadu, Gujarat and Rajasthan were the top three states for cumulative capacity. Demand for large-scale solar projects rose due to rapidly falling prices combined with strong policy support in several states and at the national level. India's rooftop solar market also expanded significantly in recent years but only accounted for about 10% of the country's total solar PV capacity at the end of 2016, hindered by financial and regulatory challenges (REN21, 2017). By the end of 2016, India planned to construct eight "green energy corridors": transmission lines to carry power from solar-rich states to high demand regions.

Figure 1. New Investment in Renewable Power and Fuels 2016 - India



Source: REN21, 2017.

3.2. Methods

I use case study methodology to examine the research questions regarding how rural renewable energy systems can promote environmental and socio-economic sustainability. 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). I extend existing theory to develop new theory (Lee, 1999). Hence, I link the literatures on sustainability with industrial ecosystems and renewable energy. Inductive case analysis is used to provide rich context and helps to understand how a renewable energy ecosystem can be designed for sustainability. Finally, the methodology reveals underlying processes by making concepts concrete (Eisenhardt and Graebner, 2007).

The case findings reported in this paper were drawn from interviews conducted as part of my Fulbright research study on the commercialization and adoption of renewable energy by base of the pyramid consumers (2013-2014). The paper also draws in general from a larger on-going study from 2009-2011 of organizations focused on commercialization processes for emerging “green technologies” in India. Interviews that informed the research 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, 2003). 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 renewable energy industrial ecosystem creation in rural India for sustainability. 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 Government of India’s 2010 Jawaharlal Nehru National Solar Mission aimed to accelerate the development and adoption of solar energy in the energy portfolio and was instrumental in developing the sector from a nascent stage to one of the largest generation based markets in the world today (Yenneti, 2016). Additionally, the government also focused on off-grid solar energy projects and introduced various schemes to provide electricity and other energy services to rural areas lacking these services. Similarly, the National Policy on Biofuels (GOI, 2009) focused 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). In this paper, I will focus on solar energy, a leading renewable energy sector in India with a policy target of 20 GW of solar capacity by 2022 (Yenneti, 2016).

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). I began with the literature on sustainability, industrial ecosystems and research on renewable energy. 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 an ecosystem for renewable energy technologies can be designed for both environmental and socio-economic sustainability. The conceptual framework is outlined in the next section.

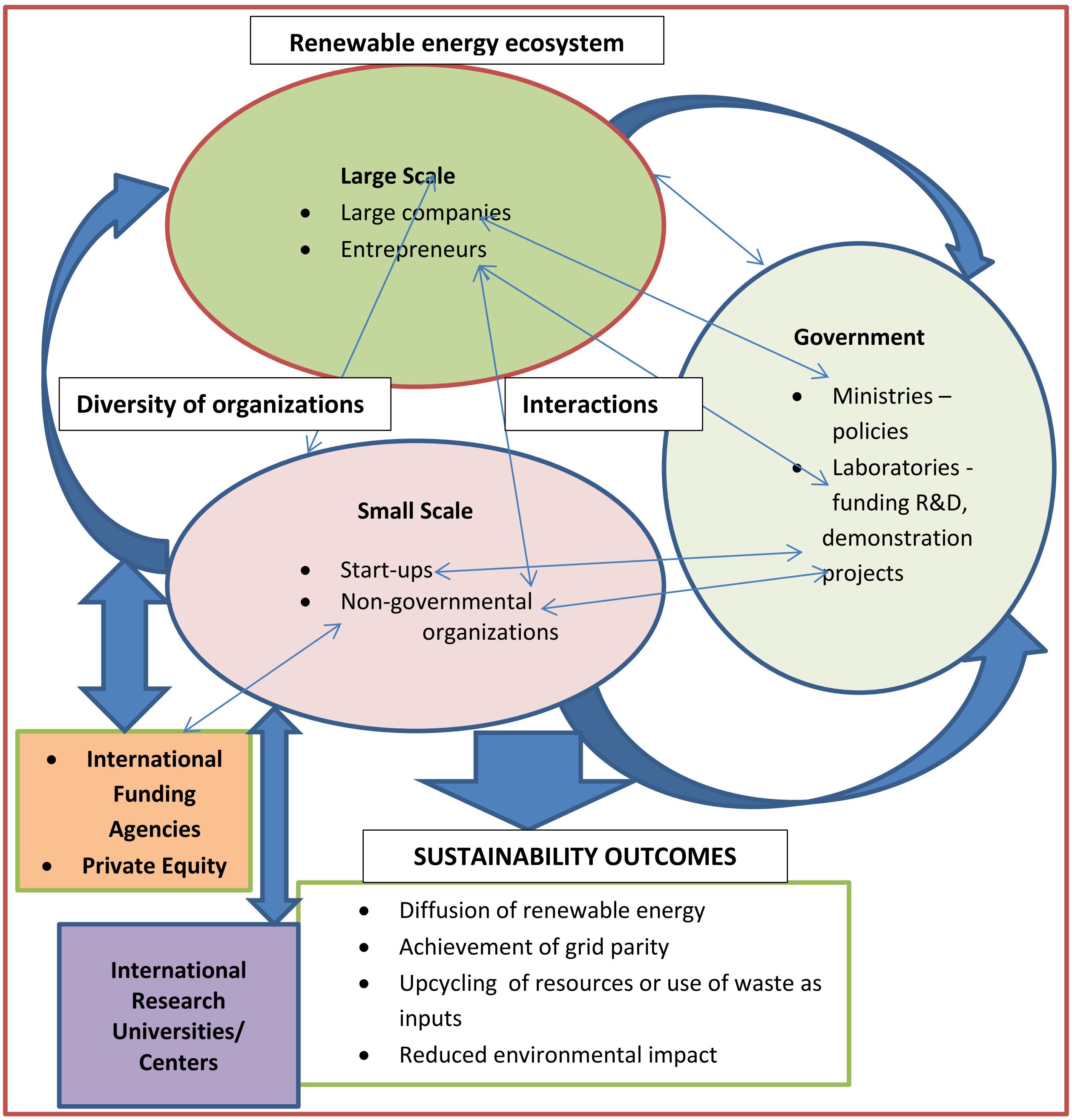
4. A FRAMEWORK FOR ESTABLISHING SUSTAINABLE RENEWABLE ENERGY ECOSYSTEMS

Drawing on theories outlined in section 2, this paper views the solar energy industry as an ecosystem and outlines a framework for sustainability in renewable energy ecosystems which can be developed through intentional, strategic and institutional pursuit of environmental goals (Baas and Boons, 2004; Chertow and Ehrenfeld, 2012). As noted earlier, ecosystems need to be socio-economically sustainable to endure over time while providing equivalent levels of wellbeing (Arrow et. al., 2010); financial stability and the creation of a social system that supports all functions and activities of the renewable energy ecosystem. Both forms of sustainability are considered: strong sustainability (conservation of all exhaustible and renewable resources without accepting substitutability among different assets); and weak sustainability, wherein the "constant capital" rule is satisfied, the assumption being that all forms of capital are interchangeable, and, hence, built capital (such as new infrastructure) and intellectual capital (such as research and development programs, new products and patents) are substitutes for natural resources (Heal, 2011).

Resilience is the ability of a system to absorb changes and still persist while stability is the ability of a system to return to an equilibrium state. Two critical aspects of ecosystems promote resilience and stability over time: (1) diversity (of species in natural ecosystems, and by extension, in industrial ecosystems); and, (2) interactions to promote resource flows amongst the members of the ecosystem as well as across ecosystems (Odum, 1969). Nurturing inter-firm exchanges or symbiosis at an early stage so that they emerge in a self-organized fashion (Chertow, 2007) can help to maintain industrial ecosystem resilience (Zhu and Ruth, 2013). Such symbiosis can be managed by moving towards circular value ecosystems (Scheel, 2016) by transforming residues or overlooked assets into valuable resources (McDonough and Baumgart, 2002).

Finally, scaling up is critical for socio-economic sustainability as larger scale affords opportunities for a variety of players to establish niches and provide different services, and reduce the impact on the environmental substantially. Such an ecosystem contributes to sustainability in the "strong sustainability" sense as it replaces fossil fuel with a renewable resource to the extent that fossil fuels and other non-renewable natural resources are not used as inputs throughout the process. In addition, the ecosystem contributes to sustainability in the "weak sustainability" sense as it also provides new infrastructure in place of the old infrastructure associated with the use of fossil fuels; moreover, it has the potential to increase intellectual capital in the form of patents, new products and services (Heal, 2011). Figure 1 below outlines how the ecosystem can contribute to sustainability, both strong and weak.

Figure 1. Sustainability in renewable energy ecosystems



5. RENEWABLE ENERGY IN INDIA: FINDINGS

The framework presented above is applied to two cases in the solar energy sector in India. The first case, BlueSky Power[1], an Indian solar energy company, indicates support for the framework.

BlueSky Power: The company was founded in 2008 by an engineer who returned to India after having obtained a business degree from the U.S., working in the software industry and founding a successful start-up in the U.S. that was eventually sold to a company in Silicon Valley. The founder-entrepreneur was interested in being involved with a socially conscious business and, after spending a year understanding the policy regime in India, decided to enter the Indian solar industry. He persisted with his project, despite early policy challenges such as the regulation that required ownership of at least 50% of the land needed for a solar project. Subsequently, the policy was changed and companies were given 180 days to obtain land after winning a project. BlueSky Power built its first grid connected solar power plant in Punjab in 2009, north of Amritsar. Interest in solar energy grew and the Jawaharlal Nehru National Solar Mission also provided a boost to the solar energy industry.

BlueSky Power engaged in interactions with a various types of organizations. Early on, the company interacted with the government by providing inputs to influence policies for solar energy. Taking advantage of the policy changes, BlueSky Power developed various projects throughout India in various states and was operating in nine states in 2014. The company signed contracts with various distribution companies that bought power from it to sell to consumers. The cost of energy for the first project was Rs. 17 per unit, and dropped to Rs. 6.5 or Rs. 7 per unit over a period of five years. Over time, in addition to contracting with the government, private contracts without government intervention became possible. Moreover, new business models were adopted for private sector projects. For example, rooftop projects were undertaken for various companies to generate solar power to be fed to the grid. This included a pan-India project with a major Indian real estate company. Working with large companies instead of individual consumers was important to ensure that the project would be of sufficient size and scale. Smaller projects were not viable because of the challenges of financing risk, construction risk, and risk of non-payment. Additionally, there was the risk of resistance from distribution companies that were already supplying power. Interactions included reaching out to leading international research institutes such as Fraunhofer-Gesellschaft in Germany for technical expertise in specific knowledge domains.

Most of the larger solar projects were set up in rural areas to promote inclusive growth and provide employment in construction and infrastructure development while generating power for these areas, most of which did not have power even if they were grid connected. Here, delivery, maintenance and application models were different but the same basic technology was deployed as in small scale

[1] The names of companies have been changed to maintain confidentiality.

projects. Taken together these helped to build the socio-economic sustainability of the solar energy ecosystem while reducing environmental impact.

EnergyAccess: Likewise, not-for-profit research organizations in India also attempted to solve the problem of energy for India's rural poor by providing lighting solutions for the urban and rural poor. These solutions depended on different business models that catered to the cost conscious and price sensitive consumer base which was not yet being serviced by the private sector. The mandate of one such not-for-profit organization, Energy Access, was to facilitate access to energy through various technologies and show that it was possible to create a market. New business models were developed by interacting with local communities, training local people to provide needed services such as maintenance and repair and facilitating the emergence of new entrepreneurial ventures such as renting solar lanterns for these communities. The rental model was appropriate because the urban and rural poor could not pay in full for solar lanterns but were willing to make a small investment to get access to better lighting. Energy Access encouraged women to become entrepreneurs and found that those who took on an entrepreneurial role became more empowered. To diffuse solar lanterns, Energy Access partnered with the government, with international agencies and foundations for funding the project, with corporate sponsors enabling them participate in corporate social responsibility related activities, with non-governmental organizations and individuals. As a result, diverse types of organizations became associated with these communities with interactions among them providing access to different kinds of knowledge and resources, and with each organization type playing a different role in the ecosystem.

A by-product of the organization's activities was that solar lanterns were adopted by villagers, the use of kerosene (a polluting and non-renewable source of energy for lighting) dropped, women increased their incomes by working in the evenings and night, and children could study away from the cook-stoves and, instead, use lanterns under a mosquito net, thus reducing their exposure to pollutants and other health hazards. Overall, Energy Access helped to improve the lives of the rural poor and build a sustainable ecosystem for solar energy.

Other types of organizations such as research organizations also participated in the solar energy ecosystem. A third example is a research organization, the *Science and Technology Center*, which provided technical information, assessment tools for Life Cycle Analysis, conducted research and development of various technologies and made policy recommendations. Such organizations generated more knowledge about the solar and renewable energy sector helping to develop its trajectory and also provide insights on its governance. For example, this organization was engaged in a project to develop solar thermal technology to be used in combination with other renewables such as biomass, thereby turning waste into energy and reducing the cost of 2-3 megawatt (MW) plants. Making these plants more cost effective and versatile with regard to the inputs would enable the achievement of scale as such plants could be installed in large numbers.

6. DISCUSSION & CONCLUSION

The paper aimed to address the question of how renewable energy systems can promote environmental and socio-economic sustainability. A framework was presented to suggest how this might be accomplished. The paper extends past research on industrial ecosystems and links it with the literature on sustainability. Additionally, it addresses how to establish renewable energy ecosystems, an under-researched and important area. Key findings from the cases suggest that besides technology improvements to reduce cost, interactions across diverse organizations in the ecosystem help to improve socio-economic and environmental sustainability. This is most likely because through their interactions, a process of discovery is activated, stimulating understanding of the context, new possibilities in the form of new entrepreneurial entry, innovations in delivering products such as solar lanterns and new technological combinations to re-use waste and reduce cost. The paper indicates that the ecosystem meets the criteria for both “strong” and “weak” forms of sustainability. The adoption of solar technologies decreased the use of fossil fuels, an effect that would be enhanced over time as the technologies are deployed on a large scale, thus complying with “strong sustainability”. At the same time, the creation of new infrastructure as well as knowledge about new technologies such as solar contributes to the built environment, and, hence, contributes to “weak sustainability”. However, while the idea of “zero waste” is implicit in the use of waste to generate energy, the ecosystem is far from being able to put all outputs (including waste) to higher value uses.

A limitation of the paper is the use of cases to develop insights. Future studies using large sample surveys could be conducted to validate the results of this research. Simulations could be developed to enhance understanding of different aspects of an industrial ecosystem. Likewise, scenario analyses could be conducted to understand how interactions across diverse organizations affect the ecosystem and its trajectory. Finally, replicating the study in other geographic locations would yield insights on the impact of context on the ecosystem.

Sustainability is of critical importance in the 21st century as human activity is rapidly depleting the resources of the natural environment and the wealth of future generations. Hence, the research is of importance to policy makers and governments, both in emerging and industrialized economies. Promoting understanding of how to establish successful ecosystems for solar energy would aid development, improve social inclusion, and reduce the cost of fossil fuel imports while increasing per capita energy consumption in addition to reducing the impact on the environment in emerging economies. Similarly, in industrialized countries, wider adoption of solar energy would lead to a cleaner environment and keep intact the natural wealth of nations.

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