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An empirical examination of the development of a solar innovation system in the United Arab Emirates

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A B S T R A C T

We apply the sectoral innovation systems (SIS) approach to analyze the emergence of a solar energy sector in the United Arab Emirates (UAE), a hydrocarbon-rich Middle Eastern nation with limited industrial and technological capabilities. Using qualitative research, we examine two research questions: (1) What is the current performance and functional patterns within the emerging solar system of innovation (SI), and (2) What are the main factors that have the potential to either sustain or potentially undermine the development of a SI in the country? Our analysis contributes to the literature in several ways. While earlier studies have focused on how the innovation process evolved in retrospect, our analysis of an emerging SI allows us to examine the current forces behind the creation of a new renewable energy industry. Our empirical examination of the UAE solar energy sector also reveals the prevalence of several blocking mechanisms, as well as a few factors that could facilitate the 'catching-up' process for the UAE solar SI, currently at its formative stage of development. These research findings may also be relevant to other Middle Eastern countries which seek a competitive position in the renewable arena but are currently in early stages of industry development.

Introduction

Abu Dhabi, the capital of the United Arab Emirates (UAE), has recently embarked on the very ambitious path of developing a technology innovation hub in the area of sustainable energy, with a particular focus on solar technologies. This goal is part of Abu Dhabi's aspiration to both diversify its economy and move toward a more knowledge-based economy. Enabling this economic transformation and diversification calls for a focus on creating an environment conducive to innovation and entrepreneurship in the field of sustainable energy. While the oil and gas industry previously supported the fast growth of the UAE, concerns about future supply levels (i.e. Peak Oil) have demonstrated the importance of economic diversification for future regional development (Bradford, 2006; UNDP, 2003). In addition, several recent reports have highlighted that the Arabian Gulf countries in general – and the UAE in particular – have the highest levels of per capita CO_2 emissions and water use in the world (UNDP, 2009; WWF, 2008). The combination of high energy demand, a desire to reduce CO_2 emissions, high solar insolation, and large uninhabited desert areas, make solar energy a potential niche for the diversification of energy generation. Focusing on solar energy as a strategic development will potentially strengthen the position of countries in the Arabian Gulf with regard to their energy industry and at the same time address sustainability and climate change issues.

In this paper, we apply the sectoral innovation system (SIS) framework to analyze the emergence of a solar energy industry in the UAE. Using qualitative research, we examine two main research questions: (1) What is the current performance and functional patterns within the emerging solar system of innovation (SI), and (2) What are the main factors that have the potential to either sustain or potentially undermine the development of a SI in the country? We argue that UAE, as a wealthy, yet developing, Middle Eastern economy (with respect to institutional, political and cultural aspects) will impose different challenges from the ones faced by developed western economies. This might, in turn, require either different institutions being put in place, or the altering of the internal functional dynamics of the SI to facilitate the process of 'catching-up'. For instance, in the United States of America and in Germany collaboration across and within different organizations (such as government, academia and the private sector) has been critical for setting the development approach of the solar industry (Colatat et al., 2009). However, the collaborative model is not very common in the UAE and the wider hydrocarbon-rich Arabian Gulf region, and deference to centralized authority prevails (IKED, 2009).

Our analysis contributes to the literature in several ways. To begin with, it has been noted that there has been limited research on the prospects for renewable energy within the hydrocarbon-rich Arabian Gulf region (Al-Saleh, 2010). Moreover, the SIS framework has traditionally been used to understand how 'already established' industries have developed and how the innovation process evolved in

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retrospect. It appears that not only has there been limited empirical application of the SIS framework to the energy sector, but there is need to further develop concepts related to SIS, particularly with regard to emerging innovation systems (Malerba, 2002, 2006). Since the UAE is at an early stage in the restructuring process, this analysis allows us to examine the current forces behind the process of setting up a knowledge-based economy and creating a renewable energy industry. In addition, given that fossil-fuel based economies run the risk of resource curse effects (Sachs and Warner, 2001), our analysis is also relevant to discussions on the potential that industrial diversification offers in reducing such risks.

We add theoretical depth to the literature by presenting an empirical application of SI frameworks in the contexts of 'emerging' and 'catching-up' as opposed to 'already established' industries. In addition, studying the challenges and opportunities for developing the solar industry[1] in the UAE will offer policy insights into how an innovation system could emerge locally, with the potential to draw relevant lessons for the greater Arabian Gulf region and any other emerging or developing economies that have an interest in creating an indigenous solar industry. Moreover, since the UAE is interested in a larger portfolio of low-carbon technologies (i.e. nuclear energy, carbon capture and utilization and storage), which also require large initial investments and government support, some findings from the analysis of the emerging solar SI could also be relevant to other sectoral strategies.

The paper is organized as follows: we start the section "Systems of innovation as a conceptual framework" with a brief literature review on the SI framework and how it can be applied to the solar energy industry in the UAE. The section "Data collection and analysis" presents our research methods and the data collection process. In the sections Structural analysis of the UAE solar innovation system and Functional analysis of the UAE solar innovation system, we discuss our findings in terms of the structural and functional analyses of the emerging solar SI in the UAE (and hence examine the potential for the successful development of a solar energy industry). The last section concludes with a summary of the main contributions of this paper, as well as directions for future research.

Systems of innovation as a conceptual framework

Traditional methods of innovation system analysis that focus mainly on identifying the structure of an SI have proved to be insufficient for understanding the factors and processes that drive and sustain innovation (Hekkert et al., 2007). In many studies, the system structures are regarded as static, "rendering them unfit to deal with technology dynamics" (Suurs and Hekkert, 2009). In an attempt to go beyond the traditional structural-oriented SI analysis, it has recently been proposed to examine the underlying processes – commonly referred to as 'functions of innovation systems' – that need to be served for a new SI to perform well. Understanding such functional dynamics has initially been proposed as a useful analytical supplement to the Technological Innovation System (TIS) approach. The notion of a technological system was originally defined by Carlsson and Stankiewicz (1991) as:

> …a dynamic network of agents interacting in a specific technology area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology (p. 94).

A TIS, by definition, is a network of *actors*, *institutions* and the interrelations between them, referred to as *networks* (Carlsson et al., 2002). In addition, rather than having a geographical starting point (as in National Innovation Systems 'NIS') or an industry (as in Sectoral Innovation Systems 'SIS'), TIS focuses on a particular technology. It might be worthwhile to briefly highlight the main structural elements of TIS: actors, institutions and networks. The term *actors* refers to the organizations and individuals involved in the emerging technology. *Institutions* can be defined as "sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals, groups and organizations" (Edquist and Johnson, 1997). Finally, *networks* are modes for the transfer of tacit and explicit knowledge (Metcalfe, 1992). Examples of networks are a coalition of firms, industry associations and research communities. Engaging in political networks facilitates institutional alignment, while being strongly integrated in a knowledge-oriented network increases the resource base of an actor and facilitates learning. The development of a TIS, as Suurs (2009) argues, depends on the coordination and interrelations between all of these actors. For instance, while governments have played a key role in supporting the development of the solar industry worldwide, the success of a TIS depends on how well those government efforts have been coordinated with the needs of entrepreneurs and the business sector.

The emergence of an SI is a long-term and uncertain process (Jacobsson and Johnson, 2000; Suurs et al., 2010). In general, TISs evolve in two main phases: a *formative* period followed by *market expansion*. Given the emerging nature of the solar industry in the UAE, the formative period is most relevant and is therefore the focus of our analysis. In the formative stage, a TIS is usually characterized by high uncertainty, weak or absent institutions and technological structures and a lack of specific actors in the SI (Jacobsson and Bergek, 2004; Suurs et al., 2010). The dynamics in the formative phase may be obstructed by factors related to weak structural elements or to exogenous factors. Furthermore, even if the formative stage is completed successfully, there are usually many difficulties in achieving transition to the expansion stage. Nevertheless, the formative stage is highly critical for attracting new actors (as part of early market formation), aligning institutions, and forming networks in the TIS, all of which are necessary conditions for transitioning to the market expansion stage (Jacobsson and Bergek, 2004).[2]

It is important to clarify that because the solar industry in the UAE is in very early stages of development, the discussion of innovation process in this paper does not focus on a specific solar technology. The vast majority of local renewable energy companies that operate in the UAE deal broadly with all solar-related technologies, without a particular emphasis on a specific type of solar energy technology (e.g. photovoltaics or concentrated solar). Such a lack of speciality should not come as a surprise given the early development stages of the solar energy industry there. In these early development stages, the institutional challenges faced and hence the policy actions to address them may be best identified with a broad sectoral focus before attempting to look into the specifics of each solar energy technology. Consequently, we define the UAE solar SI as those structural elements (and their respective functional dynamics) that directly support (or inhibit) the development and eventual diffusion of all solar energy technologies in the UAE (Carlsson et al., 2002; Suurs and Hekkert, 2009).[3]

[1] When referring to an emerging industry – such as the UAE solar energy industry – the notions 'industry' and 'sector' can sometimes be used interchangeably, as they are on occasion in this paper.

[2] Incumbent technologies are often subsidized (Jacobsson and Bergek, 2004), and a new technology requires a long period of nurturing and diffusion before it achieves a price-performance ratio that makes it attractive to larger market segments. Therefore, the creation of "protected spaces" (niche or early markets) may require government support (e.g. subsidies and investment in R&D) (Jacobsson and Johnson, 2000).

[3] The issue of 'system boundaries' has been discussed by several scholars (a review is provided by Markard and Truffer, 2008). Such discussions are inconclusive, but it is generally accepted that system boundary is largely dependent on the research questions and the scope of the analysis. For example, one of the reviewers mentioned that the work on TIS by Carlsson and Stankiewicz (1991) has led to the publications of two books (i.e. Carlsson, 1995, 1997) where the system's boundaries were expanded from the narrow perspective of TIS to almost that of the sectoral innovation system (SIS). In addition, some recent work by Bergek et al. (2008b) has attempted to bring the two perspectives together by including artifacts and technical knowledge as structural elements of the TIS concept.

It could, therefore, be argued that the application of only the technology-oriented TIS approach carries the risk of overlooking more general patterns such as knowledge development and innovation opportunities that take place at the sectoral level (Borup et al., 2007). In acknowledgment of that risk, given the emerging nature of the solar sector in the UAE, this paper has adopted the Sectoral Innovation System (SIS) approach to examine how a product, which is produced through multiple and different technologies and bodies of knowledge, ends up defining an entire sector like the solar energy industry.[4] By contrast, in a 'well-developed' renewable energy industry, one could suggest that there is a TIS centered on each of the constituent products or technologies in that industry.

Malerba (2005) has broken down the main structural elements of an SIS into: *knowledge* and *technologies*, *actors* (i.e. government, firms and other organizations), *networks*, as well as *institutions* (e.g. standards, laws and regulations). Thus, in order to understand the innovation processes of a given sector, one needs to give due consideration to these five key elements. According to conventional SIS thinking, successful new technologies emerge from a favorable combination of all these factors. Moreover, the SIS approach suggests that any sector belonging to a particular country can be characterized by a specific knowledge base, technologies and inputs. In essence, the SIS concept recognizes the fact that national sectors vary in terms of knowledge accessibility and source of technological opportunities. Therefore, it could be argued that the SIS concept – when compared to the mainstream TIS approach – does not only place more emphasis on knowledge and technological domains, but it also recognizes the fact that – within each sector – there will always be regional and country specifics that affect the different trajectories of industrial development.[5]

Since the focus of this paper lies in generating insights into the system performance and policy-relevant factors that affect the development of solar energy industries, an examination of the functional patterns as conceived within the SIS framework is needed. In this regard, Bergek et al. (2008a) argue that "[i]t is in these processes where policy–makers may need to intervene, not necessarily the set–up of the structural components" (pg. 409). Given the enormous recent interest in the system functions approach, a number of function lists have appeared in SI literature (e.g. see Bergek et al., 2008a; Johnson, 2001; Liu and White, 2001; Markard and Truffer, 2008). Although – as mentioned earlier – many of these functions were originally proposed for the TIS concept, their suitability with regard to understanding the functional dynamics of SI at industry level has also been confirmed by a number of scholars (e.g. Bergek et al., 2005; Johnson and Jacobsson, 2001). Bearing in mind that, when analyzing sustainability innovations, earlier studies have stressed the importance of a dynamic framework (Bergek, 2002; Hekkert et al., 2007; Jacobsson and Johnson, 2000; Negro et al., 2007, 2008), Fig. 1 illustrates the structure and functional dynamics of an SIS framework.

These system functions (i.e. key processes) are at the core of a well performing SI. The mutual reinforcement of these functions, through a process of cumulative causation, defines the ultimate outcome of the innovation process and is considered necessary for an SI to emerge (Suurs and Hekkert, 2009). One could therefore suggest that

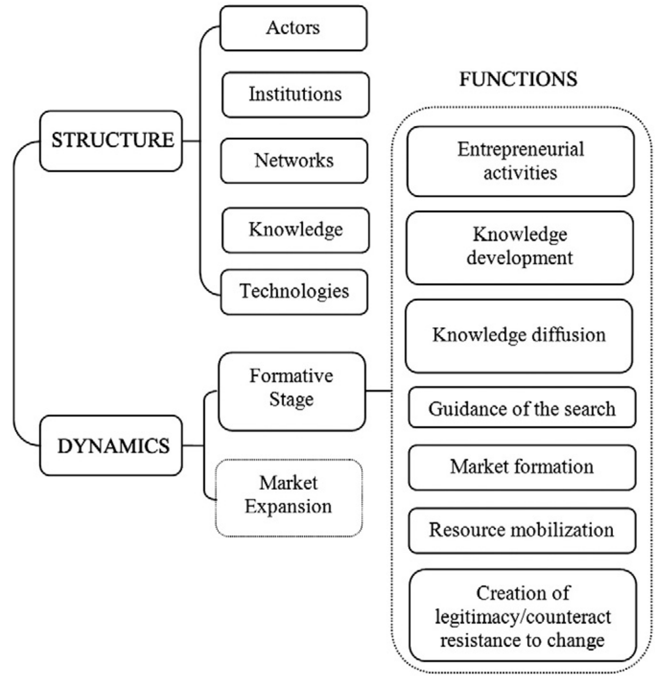

Fig. 1. The structure and functional dynamics of an SIS framework. Sources: Based on Bergek et al. (2008b); Hekkert et al. (2007); Jacobsson and Bergek (2004); Malerba (2005); Suurs (2009).

the more (and better) these functions are served, the better the development, diffusion and implementation of innovations will be. This argument is based on the assumption that the fundamental goal of the SI is to develop, diffuse and utilise innovations (Edquist, 2005; Johnson, 2001). In other words, the diffusion of a new technology (and the growth of its respective SIS) is related to the interaction dynamics between the system functions. In this regard, it has been argued in the renewable-related SI literature that positive interactions between system functions could lead to virtuous cycles in the processes of change that strengthen each other, eventually leading to the building of a momentum-creating process of creative destruction (e.g. Borup et al., 2007; Hekkert et al., 2007; Negro, 2007). It would, therefore, be interesting to gain insight – based on empirical research – into how the process of such momentum building may take place in the emerging solar energy industry of the UAE. Moreover, gaining insight into the desired build-up of such virtuous cycles would further enhance our understanding of ways to promote the successful diffusion of solar energy technologies in the UAE.

Data collection and analysis

On the methodological front, it should be recognized that there are different 'quantitative' methods for studying a 'well-established' SI; for example, patent data could be used to identify relevant actors (and to some extent their competences). However, when examining the case of an emerging SI, mapping out potentially active actors might perhaps only be possible 'qualitatively' by delving into informed sources of information. In our case, a database for companies involved in the UAE solar industry was created through a combination of government records searches, Internet site visits and personal communications. The empirical data for this study was collected primarily from expert interviews that took place between February and August of 2009. In total, twenty semi-structured interviews were conducted with various experts in the solar energy field throughout the UAE, including business owners, government officials and representatives of local utilities. The interviewees (80% of whom work in the private sector and 20% in the public sector) were all of

[4] As observed by one of the anonymous reviewers, TIS studies usually assume that since technology production or demand markets tend to exist in geographical proximity to each other, the focus is often placed on both production and demand aspects. It should be noted, however, that – especially when examining the case of the global solar PV industry – the demand is not necessarily concentrated in regions that manufacture the largest shares of PV technologies worldwide. Given the early development stage of the UAE solar industry, this paper focuses on both technology production and demand at the sectoral level.

[5] Along these lines, and given the importance of knowledge creation in the SIS concept, Sovacool (2010, p. 924) stresses that approaches to energy research "are contingent and connected to political and social priorities, methods of research, market forces, and broader cultural values and consumer attitudes."

senior status (e.g. Chief Executive Officers, business owners, and senior managers). The UAE consists of seven states (known as 'emirates'), and 75% of the interviews were conducted in the major emirates of Abu Dhabi and Dubai, which are the homes for most solar companies in the country. More specifically, ten interviews were conducted in Abu Dhabi, five in Dubai, two in Sharjah and a single interview in each of the emirates of Ajman, Fujairah and Ras Al-Khaima.

Interviews were tape-recorded, transcribed, coded and analyzed using a commercially available software package named Nvivo. Using this qualitative analysis software was useful in terms of classifying and categorizing data, and in searching for an exact word or words that are similar in meaning in the interviews' transcripts. An effort was also made to identify a chronological list of events, match them to the structures and functions of the SIS under consideration, and then identify interactions between the different events, actors and functions. Such an inductive approach allowed us to gain an in-depth understanding of the structure and the emerging functional dynamics in the emerging solar energy SI in the UAE. More specifically, the findings of the interviews have provided a source of information with which to carry out structural and functional analyses, which are presented next.

Structural analysis of the UAE solar innovation system

As previously shown in Fig. 1, structural analysis of any SIS would essentially require the consideration of five elements (i.e. actors, institutions, networks, knowledge and technologies). Given that the focus of this paper is on assessing the performance and functional patterns within the emerging solar SI in the UAE, what follows is simply a brief outline of the structural elements of the SI under consideration. Such an outline will be helpful in terms of establishing an understanding of the main actors and key networks operating in the UAE solar SI, as well as the current status of knowledge, technologies, and relevant institutional frameworks.

Actors

From the outset, it is important to recognize that the UAE is a monarchy that remains deeply committed to traditional tribal roles and cultural patterns. As a result, the government (i.e. the ruling elite of the royal family) acts as a strongly paternalistic and omnipotent decision maker, decisions being made primarily at the highest levels of government authority. This characteristic differentiates the UAE's governance model from many other developed and developing countries. Table 1 provides a list of only the main actors in the solar energy SI in the UAE. Subsequently we discuss in more detail those actors that play the largest role in the current developments.

Table 1
The main actors in the emerging solar energy SI in the UAE.

Category	Main actors
Government	Abu Dhabi Executive Council Federal National Council
Energy sector	Federal Electricity and Water Authority Abu Dhabi Water and Electricity Company (and the other regional agencies) Regulation and Supervision Bureau Environment Agency — Abu Dhabi
Private sector/ companies	Masdar Other companies with operations in the region (see Table 2)
Financiers	Abu Dhabi Future Energy Company/Mubadala Investment Company Masdar Capital
Education and research	Masdar Institute for Science and Technology UAE University in Al Ain (and other local universities)
Business networks	Emirates Solar Industry Association
Civil society	Emirates Wildlife Society–World Wildlife Fund in Abu Dhabi

Table 2
Private companies involved in the solar industry in the UAE by stage in the value chain.

Stage in the value chain	Number
Downstream	
Installation and other activities*	44
Trading only	28
Upstream	
Assembly	1
Manufacturing	4
Total	77

* Note: This category includes companies involved in several of the following activities: consulting, design, installation, maintenance, turnkey and system integration.

Given the very early stage of industry development in the UAE, our empirical research has contributed to identifying the baseline in terms of actors present. The research findings allowed us to create a national database of seventy-two private companies with activities in the solar industry. Most companies are concentrated downstream (e.g. design, installation, maintenance, system integration) (see Table 2). Lack of specialization among these companies can be linked to the small size of the market as well as their modest resources. Only four of these seventy-two companies currently manufacture solar products — namely solar photovoltaics (PV) cells, solar collector mirrors and solar thermal collectors. We also identified sixteen consultancy companies offering various related services and four investment companies that could potentially provide funds for renewable energy initiatives. In total, 75% of the companies identified are located in Abu Dhabi and Dubai, while the remaining 25% are scattered across the other five emirates.[6]

The main player, by size of investment and diversity of technologies is the Masdar Initiative, which was launched by the UAE Government in 2006.[7] With a current budget of US$ 16 billion, the project is driven by the Abu Dhabi Future Energy Company, a subsidiary of the state-owned Mubadala Investment Company.[8] Landmark projects that are part of this initiative are the development of Masdar City – a carbon-neutral residential/work community and industrial and R&D cluster – which will also host the headquarters of the newly established International Renewable Energy Agency (IRENA). Another unit of the Masdar Initiative is the Masdar Institute of Science and Technology (Masdar Institute), which is a graduate research university that has recently been established in collaboration with the Massachusetts Institute of Technology.

Bearing in mind the potential role that universities can play in supporting the establishment of new industries, it is important to note that the Masdar Institute is currently the only academic establishment that focuses its curriculum on advanced energy and sustainability. Here, it is perhaps worth highlighting the severe lack of governmental research funding agencies in the UAE — as is the case with most Middle Eastern countries. The National Research Foundation has been established in 2008 to support R&D activities in various fields.[9] Other government-sponsored funds are the Sheikh Khalifa

[6] Given the emerging nature of the solar industry in the UAE, only a few of these companies are multinationals with local presence. Most companies are local businesses that have diversified their operations into the downstream part of the solar industry value chain or small businesses focused entirely on solar energy and serving the larger Arabian Gulf region (i.e. installation, assembly or manufacturing).

[7] The Masdar Initiative includes five units: Masdar Institute, Masdar City, Masdar Carbon, Masdar Power and Masdar Capital. More details about the initiative can be found at www.masdar.ae.

[8] The initial budget for the project was US$ 22 billion. However, in light of the global financial crisis the investment plan for the Masdar Initiative has been recently reassessed (Stromsta, 2011a).

[9] Significant delays occurred in the disbursement of funds since early 2009 when the first projects were awarded. Finally, in November 2011 the initially committed funds have been distributed.

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Fund for support and Development of Small and Medium Enterprises (in Abu Dhabi), Emirates Foundation, and the Sheikh Mohammed bin Rashid Al Maktoom Foundation (in Dubai), although not specific to energy-related projects. In addition, recognizing the "underdeveloped research and innovation environment" in the UAE, the Abu Dhabi Education Council has also proposed the set-up of a research funding agency (ADEC, 2010). Nevertheless, it has become apparent from the interviews conducted that even long before the global economic downturn, UAE-based funding for solar energy companies was difficult to secure. One identified reason is that UAE finance agencies were not familiar with renewable-based businesses. According to one of the interviewees, "[w]e had to teach the bank what solar meant, literally".

Another group of actors that have the potential to play a critical part in the emerging solar SI are the utility companies. The Federal Electricity and Water Authority (FEWA) is the entity responsible for overseeing federal utilities, while three separate governmental authorities in the three major emirates (namely Abu Dhabi Water and Electricity Authority 'ADWEA', Dubai Electricity and Water Authority 'DEWA' and Sharjah Electricity and Water Authority 'SEWA') oversee power and water generation in their respective emirates.[10] However, the Northern emirates (especially Fujairah), served by FEWA, have been faced with severe power shortages over the past few years as the existing grid does not cover the increasing energy demand.[11] It has emerged from our interviews that the Northern emirates are considering setting up their own electricity and water authorities, so they will no longer be dependent on FEWA for the provision of power. Given the lack of involvement on the part of the private sector in the current UAE power market, it is hoped that the state-owned utilities would start to use solar energy technologies to generate electricity and water in the country, and hence contribute towards solar market development.[12]

Another potentially relevant actor – identified in the emirate of Abu Dhabi – is the Regulation and Supervision Bureau (RSB), which is responsible for the regulatory framework for tariffs for electricity, water and wastewater, as well as a variety of overarching issues.[13] It appears, however, that although RSB is charged with establishing tariffs and charges, it is Abu Dhabi's eighteen-member Executive Council (the executive authority) that actually decides upon these costs. Therefore, this becomes important when considering the decision making process for solar energy in this Middle Eastern country.

Institutions

As previously indicated, within the realm of innovation studies the term 'institutions' refers to both the 'social norms' as well as the 'regulations' that shape and regulate the behavior and interaction between actors (Edquist and Johnson, 1997). During the interviews there was frequent reference to behavioral features of Arab culture, such as high levels of risk avoidance (and fear of blame), high centralization of authority, and high respect for authority, that can inhibit creativity and the transition to an innovation-based economy in the UAE. However, some of these same features, such as deference to authority can also potentially support innovation, because if top leaders strongly encourage innovation, their followers will be motivated to act accordingly. There have been numerous announcements that UAE leaders are, in fact, supportive of innovation in solar and other forms of renewable energy. Speaking about what motivates the decisions of the UAE royal family, one of the interviewees stated, "[t]hey want something which is absolutely innovative, that nobody has done before, and they don't mind about the money. They are billionaires". This is a potentially encouraging indicator, especially when bearing in mind that the UAE is committed to traditional tribal roles in which the ruling elite is the omnipotent decision maker in the country. Nonetheless, our in-depth interviews suggest that there is an incidence of 'psychological defeat' or 'lack of self-esteem' in local expertise and capabilities. Another theme emerging from the interviews is the prevalence of 'a strong trader mentality', which originated from traditional Arab culture. This mentality can inhibit innovation when it encourages a focus on short-term financial returns as opposed to the long-term perspective needed for achieving potential gains from research and development (R&D), entrepreneurship, and for building indigenous technological capabilities in the emerging solar sector.

With regard to regulations it is important to note that – due to generous subsidies offered by the UAE Government – the current prices of electricity, water and gas are very low. Current domestic electricity tariffs for UAE nationals range between $.008 and $.013/kWh (depending upon the remoteness of the area), and $.041/kWh for non-nationals. Water tariffs are also low; while water is supplied free of charge to the homes of UAE nationals, foreigners are charged only $2.6/TIG 'Thousand Imperial Gallons' (RSB, 2011). These tariffs do not distinguish between the time of day (or time of year), nor is there any adjustment based on the customer's consumption level. Such tariffs are indeed very low when compared with other countries. For example, while electricity tariffs in the UAE range between $0.01 and $0.04/kWh, the tariff in the USA averages around $0.11/kWh — which is in turn lower than many European countries (EIA, 2010). It is apparent that these subsidized electricity prices hinder adoption of solar technologies in the UAE. According to an interviewed Masdar associate, the current solar PV selling price results in an electricity cost of around $0.45–55/kWh, which is more than ten times the rate that UAE electricity users currently pay. However, Masdar seems to be committed to expanding its solar energy applications in order to meet a 7% Renewable Portfolio Standard (RPS) target (by 2020) set by Abu Dhabi's government. In addition, Masdar has recently signed a Memorandum of Understanding (MoU) with the Ministry of Education and Abu Dhabi Education Council in order to incorporate the subjects of renewables and sustainability in UAE educational curricula (Masdar, 2009).

Networks

Masdar is clearly the driving force in the development of the solar energy industry in the UAE. Our interviews suggest, however, that there is limited interaction and coordination between the different innovation system actors (e.g. local solar companies, financiers, utilities, other government agencies, and Masdar). Hence, strategic decisions regarding industry development tend to lack transparency. In an effort to bridge this lack of communication and coordination, under the initial guidance of the Masdar Institute (as a neutral education and research organization), a group of local companies came together in late 2009 to form an industry association (Emirates Solar Industry Association, 'ESIA') to promote solar energy in the region and foster closer collaboration.

Knowledge

Although there are a small number of private industry experts with solar-related knowledge working in the UAE, our research

[10] For example, ADWEA serves as an umbrella organization that sits over four other legal entities which together are responsible for the generation of power (ADWEC), production of potable water, transmission and dispatch, distribution of power and water, and wastewater collection, treatment and disposal.

[11] The main challenge for the Northern emirates is that only 20 to 30% of the commercial buildings are connected to the general power grid and that since 2006 the demand for electricity in this region has been rising as much as 25% per year, far beyond FEWA's plans to provide for a 7% increase in power demand (Salama, 2010).

[12] It is reported that FEWA has signed an agreement with Masdar to supply the federal grid with electricity from renewables and nuclear energy (which is expected to start generating power in 2017) (Salama, 2010). Nevertheless, it is unclear whether this plan is likely to solve the power shortages in the Northern emirates.

[13] For instance the connection of the 10 MW solar PV power plant to Abu Dhabi's electrical grid was a joint effort by Masdar, Abu Dhabi Distribution Company (ADDC) and the RSB.

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revealed that at present, a wider solar-related knowledge base hardly exists among the indigenous population in the country. Knowledge with regard to solar energy is expected to increase, however, with the establishment of the Masdar Institute, which began teaching its renewable-oriented postgraduate curricula in 2009. The lack of solar-related knowledge is a reflection of problems in the development of a wider scientific knowledge base across the region. Discouraging indicators which have been reported in the literature (e.g. Arab Science and Technology Foundation, 2010; Lord, 2008; Naim, 2006; The World Bank, 2010) include a modest number of patents, a limited number of local scientists working in R&D, and a severe lack of R&D funding with an almost absent contribution from the private sector. However, growth of the UAE knowledge base in general is a goal of current UAE leaders. For example, ambitious plans (e.g. as part of the UAE Vision 2021; and Abu Dhabi's Economic Vision 2030) have recently been announced to develop a knowledge-based economy in the region (The Government of Abu Dhabi, 2008). While these plans are a positive sign, at present the solar-related knowledge base is still notably inadequate. However, bearing in mind the considerable financial resources of the country, engaging in international knowledge and technology sourcing seems as a viable catching-up opportunity for knowledge development.

Technologies

According to Bergek et al. (2008a), the structural element of 'technology' refers to two interrelated meanings: (i) technical knowledge and (ii) artifacts — material and immaterial objects that can be used to solve real-world technical problems. Malerba (2004) explained this structural element in detail when he introduced the concept of SIS, and he argued that this should refer to all factors related to the technological base of the SI under consideration, e.g. technological opportunities and cumulativeness. Bearing in mind the underdeveloped technological status and solar-related capabilities in the UAE, coupled with an almost total reliance on foreign technologies.

Given the lack of knowledge in these technologies, as discussed in Section Knowledge, the reliance on foreign expertise is critical for the emerging stage of the solar sector in the UAE. As mentioned earlier in the paper, UAE aims to develop both the production capabilities as well as its market potential. On the production side, Masdar Initiative has invested 150 million Euros in setting up a manufacturing plant, Masdar PV, to produce silicon-based thin-film PV modules, with an annual production capacity of 85 MW. Masdar PV, created in 2008, is currently based in Germany's Solar Valley, relying entirely on German management and technological expertise. Since 2009, when production has started at the facility, Masdar PV has sold its modules to customers in Germany, Canada, and India. Initially, Masdar PV had intended to open a second manufacturing facility in Abu Dhabi in 2010, but these plans had been recently canceled (Hashem, 2011). This change in plans has been attributed primarily to lower local and regional demand than initially expected, and the high level of subsidization for conventional fuels (Stromsta, 2011b). Nevertheless, by locating manufacturing in Germany while investing in research in Abu Dhabi (through the Masdar Institute) the R&D activities have been essentially separated.[14] Hence, it remains to be seen how to best integrate knowledge development with industry development (as well as deployment), identified to be important in successful innovation systems in both the developed and the developing world (Lundvall et al., 2009).

On the market development side, the following is an account of the potential for and applications of solar technologies in the country. Solar power has great potential for renewable energy power production in the UAE given that the sun shines most of the year, and that the UAE has vast amounts of uninhabited desert land. The UAE is located in area usually referred to as 'the most favorable solar belt' – between latitudes of 15°N and 35°N – which is naturally endowed with the best conditions for solar energy technologies. According to the German Aerospace Center, direct normal solar irradiance is estimated to be 2200 kWh per m^2 per year (DLR, 2005). A further review of solar data banks (e.g. Solar Energy Mining, 2010) confirms that such a solar irradiance figure is among the highest in the world. In spite of these advantageous conditions, solar power applications have to date been limited to parking meters, off shore buoys, traffic lights and solar-based water heating in some hotels. With the absence of statistics detailing the installed solar power capacity is in this part of the world, it might be worth pointing out here the most notable solar energy applications in the country.

At present, the largest solar PV array has recently been built at Masdar City. With an installed capacity of 10 MW, this PV (50% thin film; 50% poly crystalline) plant is the largest grid-connected solar power plant in the Middle East region. One of the interviewed Masdar associates spoke about his experience with regard to the operation of PV solar panels in the harsh environment of the UAE. Although the panels seem to be operating well, the humid and dusty environment creates the need to clean them on a daily basis to maintain their running efficiency. The measures that are currently under consideration include looking into cost-effective ways for capturing the water used for cleaning, in order to treat and re-use it. Back in 2008, Masdar conducted a large field study where the products of some twenty-two solar panel manufacturers were tested – for the first time – in order to determine how their different technologies endured the effects of heat, humidity and sand over a period of eighteen months. This study could also be viewed as a promising first step in developing an indigenous solar-related technological capability in the UAE.

In addition to the Masdar City 10 MW solar array, four small-scale PV projects have recently been completed in Abu Dhabi: (i) 1 MW PV rooftop installation on the Masdar Institute; (ii) 291 kW PV array at the Yas Marina Circuit; (iii) 204 kW PV parking shade structure at Masdar City; (iv) 200 kW rooftop mounted on the Presidential Sea Palace. In addition, construction contracts for a 100 MW PV plant in the city of Al Ain, named *Noor 1*, are expected to be awarded in December 2011 (Bloomberg, 2011). Another interesting activity has been the construction and operation of a 100 kW beam-down pilot plant, as a demonstration and research site run by the Masdar Institute in collaboration with the Tokyo Institute of Technology in 2009. More recently, a joint venture between Masdar (60%), Abengoa Solar (20%) and Total (20%) was awarded the contract to build a 100 MW solar thermal (concentrated solar power 'CSP') plant, named *Shams 1*. When the Shams 1 plant will be delivered in 2012, its power production will be sold to ADWEC under a long-term electricity sales contract. Shams 2 is expected to be commissioned in 2011, and Shams 3 is in design stage.

To sum up, our structural analysis of the UAE solar energy sector reveals that despite the existence of a few promising indicators and ambitious plans, the structural elements of the UAE solar SI do not yet seem to be strongly linked. Specifically, since the industry has not yet gained sufficient momentum, most solar energy related initiatives are initiated and coordinated by the Masdar Initiative units, with limited involvement of other players (e.g. private sector, venture capital). In addition, the knowledge and indigenous technological capabilities in the field of solar energy are under-developed as larger national research funding schemes have not yet materialized. Hence, an integrated approach is needed to bring these structural components together to function as innovation system. Having established a basic understanding of the structural elements of the SI under consideration, the next section analyzes its functionality.

Functional analysis of the UAE solar innovation system

The development of the solar SI in the UAE is essentially in its formative stage. In this analysis we initially focus on mechanisms that

[14] We are grateful to one of the reviewers for pointing out this issue.

could either promote or inhibit the development of a supporting SI, and then explore possible reinforcing cycles that could facilitate the establishment of a well-functioning solar sector in the UAE. The idea of conducting such a prospective functional analysis, after assessing the strengths and weaknesses of current functions in terms of driving and blocking mechanisms, was originally proposed by Bergek et al. (2008a, 2008c).

Based on data from expert interviews, synthesized by the authors, Table 3 provides a summary of the policy-relevant inducement mechanisms (i.e. drivers) and blocking mechanisms (i.e. systemic barriers) that currently affect the seven previously identified functions (i.e. key processes); and ultimately, the development of a solar energy industry in the UAE.

Obvious reasons for pursuing the solar energy agenda are abundant solar resources and financial resources (i.e. availability of petrodollars). Our research findings also indicate the existence of promising inducement mechanisms such the government's intentions to develop both a sustainable energy future and a knowledge-based economy in the UAE. The current performance of certain functions (e.g. *Guidance of the Search* and *Creation of Legitimacy*) seems to be better than others (e.g. *Entrepreneurial Activities* and *Market Formation*) because of the existence of more and stronger inducement mechanisms to support their functioning. However, despite the fact that the strengths of such inducement mechanisms outperform those in other Middle Eastern countries, these inducement mechanisms are still modest when compared to leading developed countries in the renewable energy field.

Moreover, our functional analysis of the emerging UAE solar SI has revealed the existence of numerous barriers that are currently hindering *Entrepreneurial Activities* (e.g. lack of start-up finance and a risk-averse attitude from potential lenders); *Knowledge Development* (e.g. under-developed scientific capabilities); *Knowledge Diffusion* (e.g. concentration of projects in Masdar and severely limited collaboration among other actors); *Guidance of the Search* (e.g. lack of transparency in policy-making); *Market Formation* (e.g. large subsidies for conventional energy and lack of incentives policy programs for solar); *Resource Mobilization* (e.g. limited presence of both R&D funding and awareness with regard to renewables among investors and banks); and *Creation of Legitimacy* (e.g. vested interests in fossil fuels and limited coverage on the subject of renewables in educational curricula). If these blocking mechanisms are not adequately addressed, they are likely to impede positive interactions within the slowly emerging UAE solar SI and hence potentially create negative prospects for establishing a solar energy industry in the country.

Considering that the seven functions need to be collectively in operation for an emerging SIS to perform well, it is apparent that given the scale and strength of the blocking mechanisms, the UAE solar SI is *under performing*. In this regard, one could argue that policymakers should focus on remedying poor functionality, either through adding/increasing the strength of inducement mechanisms or removing/reducing the force of the blocking mechanisms that have such a pervasive effect. However, prescribing a list of policy guidelines should not be the ultimate outcome of SI-based studies, which are sometimes criticized for their emphasis on studying static systems rather than analyzing systemic changes.[15] One way of overcoming such a legitimate concern is to explore ways in which positive interactions between various systemic functions could lead to 'virtuous cycles' in the process of change that strengthen and positively reinforce

Table 3
Inducement and blocking mechanisms currently affecting the functionality of the UAE solar SI (source: expert interviews).

Function	Inducement mechanism	Blocking mechanism
Entrepreneurial activities	• Masdar conducted a few field studies and experiments on renewable energy technologies. These experiments also contribute to the second function (i.e. learning)	• Limited start-up finance • Risk averse attitudes • Mistrust among actors due to weak enforcement of IPRs • Lack of technical standards and quality control
Knowledge development (Learning)	• A desire to develop a knowledge-based economy • The establishment of the Masdar Institute • Collaborations with leading foreign actors • A strong presence of foreign expertise in the UAE	• Non-existence of national research laboratories, testing and certification centers • Under developed renewable-related indigenous capabilities • Lack of self-esteem in local expertise and capabilities
Knowledge diffusion	• A desire to develop a knowledge-based economy • The establishment of the Emirates Solar Industry Association (ESIA) • Organizing several conferences and workshops, including the World Future Energy Summit	• Solar energy projects are mainly concentrated at Masdar • Limited collaboration and communication (and hence knowledge transfer) between stakeholders (including those from government, industry and academia)
Guidance of the search	• Strong government buy-in to the sustainable energy agenda, driven by a recognition for the need to diversify energy and income sources • A Renewable Portfolio Standard (RPS) in place for Abu Dhabi to achieve a renewable energy target of 7% by 2020	• Policymaking and strategic decision making with regard to industry development tends to lack transparency • Abu Dhabi's RPS target is not high enough to encourage projects outside of Masdar's current plans • Limited opportunities for competitors to leverage RPS for market development
Market formation	• A relatively inviting investment environment, especially when compared to other Middle Eastern nations • Abu Dhabi's RPS target could stimulate the creation of solar energy markets	• Lack of standardized incentives for solar power (e.g. incentives are negotiated on a case-by-case basis; there are no feed-in-tariffs; no tax environment means tax incentives not applicable) • High subsidies for conventional energy • Delays in regulatory and administrative dealings (i.e. a high level of bureaucracy)
Resource mobilization	• A hydrocarbon-rich country, hence plentiful financial resources • Availability of strong solar resources	• Lack of both renewable energy experts and a skilled workforce (i.e. underdeveloped human capital) • Very limited R&D funding (both from government and private sector) • Lack of knowledge of (and hence confidence in) renewables on the part of investors and banks
Creation of legitimacy	• Hosting the headquarters of the newly established IRENA • Signing of a MoU between Masdar, the Ministry of Education and Abu Dhabi Education Council to develop programs focused on enhancing awareness with regard to renewables in UAE educational establishments • An initiative named 'Heroes of the UAE' was launched to enhance environmental awareness among UAE youngsters	• Strong vested interests in fossil fuels • Lack of confidence with regard to renewable energy technologies among the general public • Increased interest in developing nuclear energy in the UAE

[15] It appears that the SI framework – even when supplemented with functional analysis – lends itself to static systems thinking rather than the analysis of change, contestation and transformation, which in effect have been the essence of Schumpeter's notion of 'creative destruction'. For this reason, and consistent with the evolutionary theory of economics, Schumpeter (1942) argued that it is dangerous for economists to prescribe 'general' recipes and nostrums for reform, because political and social circumstances are always changing. This is why it is important to emphasize the futility of the search for a 'magic policy recipe' that guarantees the emergence of solar energy within the UAE.

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each other, and eventually lead to the building of a momentum-creating process of creative destruction within the incumbent system. Gaining an insight into the desired build-up of such virtuous cycles could enhance policymaking decisions with regard to the creation of plausible windows of catch-up opportunities for successfully developing a solar energy industry in a country (Al-Saleh, 2010). In this paper, this prospective functional analysis has been carried out after analyzing the findings emerging from the twenty in-depth interviews, which have informed our understanding of the existing and plausible functional patterns within the SI under consideration.

While several fruitful interactions between the system functions can take place, when considering the case of the UAE, the most feasible approach appears to be to follow a top-down route, which is the preferred method for change in Arab culture. This makes the case of the UAE different from western societies, where there is a potential for community-led initiatives and interest groups to bring out grassroots innovation. For example, Hekkert et al. (2007) reported on the positive effect that lobbying, by German and Dutch entrepreneurs, has played on promoting renewable energy technologies in Germany and the Netherlands. Here, an effective starting point would be for the UAE government to set a time-bound target for adding a specific percentage of solar power to the national grid. Thinking in terms of the SI function-based theoretical framework, such an action would be referred to as *Guidance of the Search*. It is true that the Government of Abu Dhabi has already set a 7% RPS target by 2020, but that is not a legally binding target. Our analysis suggests that setting a legally-binding policy target for solar would lead to both the allocation of supporting financial resources (*Resource Mobilization*) and the enhancement of legitimacy with regard to solar power across the country (*Creation of Legitimacy*). In essence, this intervention would send a clear signal that the UAE Government is serious about the intentions to both lessen its vested interests in fossil fuels and develop a knowledge-based economy, which regards pursuing the sustainable energy agenda as a central ingredient of such an innovation-led transformation. In addition, several interviewees argued that once the UAE government commits to a legally binding policy target (*Guidance of the Search*) the solar energy industry would rapidly develop as a result.

Fig. 2 illustrates these potential virtuous cycles, which are likely to follow from a sustained governmental buy-in to solar energy in the UAE. Nevertheless, one cannot overemphasize the futility of the search for a single pattern of functional interrelations to assure a well-performing SI (i.e. to ultimately guarantee the emergence of a fully-fledged UAE solar energy industry). In effect, the range of possibilities for any innovational activity constantly changes in a way that cannot be predicted with any great confidence.

As shown in Fig. 2, our interviews suggest that governmental buy-in to solar power could diffuse knowledge and stimulate awareness of the importance of solar energy technologies, either through the educational curriculum or media channels, both of which are tightly controlled by the authorities. This outcome could further enhance legitimacy and mobilize resources, which could support knowledge development — a function that is now limited due to lack of research funds and underdeveloped solar-related technological capabilities. Knowledge development could further enhance resource mobilization in the form of human capital, by expanding local expertise and capabilities in solar-related technologies. Other possible outcomes that could result from the royal elite's support of renewables are the provision of attractive incentives and the creation of 'protected' niche markets, which in turn contribute towards both boosting entrepreneurial activities and enhancing related knowledge development. While the Masdar project, especially upon its completion, could well serve the purpose of niche markets, there is still a need to create such protected spaces in Dubai and the other emirates. One would then hope that these protected niches would feed their innovative dynamics beyond their borders (i.e. achieve a transition from the formative stage to the market expansion stage) in order to create momentum for progress.

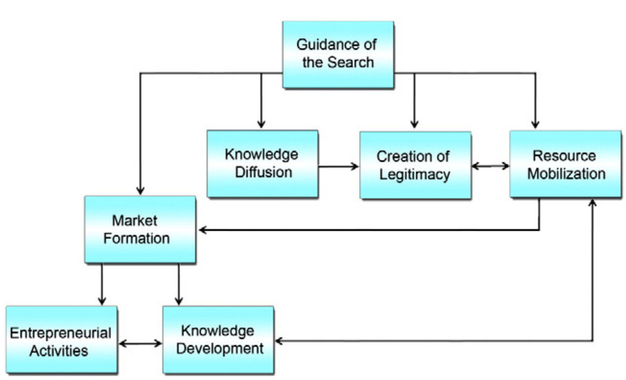

Fig. 2. Possible reinforcing virtuous cycles to stimulate the diffusion of solar energy in the UAE.

Concluding remarks

The aim of this paper was to examine the development of the solar industry in the UAE, and provide insights into the performance and functional patterns of an SIS under formation. More specifically, two main research questions have been addressed: (1) What is the current performance and functional patterns within the emerging solar SI in the UAE, and (2) What are the main factors that have the potential to either sustain or potentially undermine the development of a SI in the country? In this section, we provide a summary of the key research findings and a discussion of the implications for policy-makers in designing intervention strategies to support the development of the solar energy sector.

The emergence of renewable energy industries is a complex process that is yet not fully understood. In this regard, this paper has contributed to an improved understanding of the formative phase of SIS and has identified policy challenges associated with the process of catching-up. On the theoretical front, we have argued that when studying the emergence of new industries – at least as a first step – there is a need to go beyond the TIS approach, and think how a product, which is produced through multiple technological bases and bodies of knowledge, ends up defining an emerging SIS such as the UAE solar industry. At a later stage, when the industry is more developed, one could look in more detail at technology-specific innovation processes and diffusion prospects of a particular solar energy technology such as solar PV or CSP. To that end, we have argued that for an emerging SIS to develop and perform well, not only does it need a favorable combination of the five SIS structural elements, but there is also a need to have all functions served. In moving forward, one needs to assess and prioritize what are the most important blocking mechanisms (or systemic barriers) to be tackled in the near term and what are the issues that need to be addressed in the medium and long term. The experience of leading countries in the renewables field, such as Germany, which succeeded in establishing both an industry cluster as well as building a well-functioning SI (e.g. see Jacobsson and Lauber, 2006), suggest that multiple aspects need to be addressed simultaneously rather than on a piecemeal basis.

It appears, however, that the roles played by the SI within developing nations – including Middle Eastern ones – are likely to differ from those found in developed countries. From a developing country's SI policy perspective, there is a need to seek – at least initially – international technology sourcing and knowledge linkages in order to develop indigenous innovation capabilities. The case of the UAE is illustrative for this point, where all its current projects rely extensively on foreign expertise. The challenge, however, is how to transition to the next phase where a substantial knowledge transfer takes place to enable local capacity building.

Our empirical analysis of the emerging UAE solar SI suggests that although signs for most functions are present, they are hampered by significant blocking mechanisms and challenges such as an underdeveloped solar-related knowledge base, the presence of risk-averse and short-term investment attitudes, insufficient coordination between different actors and strong vested interests in fossil fuels. For example, given the high subsidization of conventional energy within all Middle Eastern hydrocarbon-rich countries, solar energy is at present economically unattractive for both potential users and investors. The paper also reveals the strong role of government as an important catalyst for establishing a solar energy industry in this region. The most effective action to stimulate the development of a solar SI in the UAE seems to be setting a legally and time-bound target for adding a specific percentage of solar power to the national grid. Nonetheless, if the capacity of other actors – such as universities and entrepreneurs – is not sufficiently leveraged, the effect of government actions could be significantly curtailed. Hence, creating networks of communication and collaboration for knowledge transfer and exchange of ideas is critical in providing support for the appropriate dynamics. It is noted that, in many countries, the development of a solar energy industry involves a political decision backed up by public support at the grass-roots level as well as fruitful collaboration and interaction between the government, academia and business. In the UAE and other Middle Eastern nations, however, not only does policy-making favor top-down approaches, it also lacks a strong civil society and transparency.

While this paper has focused primarily on understanding the different structural elements and functional patterns within an emerging solar SI, as well as the challenges and opportunities for catch-up leading to the development of a thriving solar industry in the UAE, further research is needed to understand the local innovation process in more detail. For instance, given the current challenges faced on developing both the production and demand side of the solar sector, more in-depth research would be needed to assess what could be the comparative advantage of UAE, and how to best harness it for the future development of a solar energy sector. Additional research endeavors are also needed to assess the knowledge production dynamics in the UAE, social aspects related to entrepreneurial culture and the type of policies that are likely to trigger the desired results in the transformation process to sustainability-oriented and knowledge-based economies within Arabian Gulf monarchies. After all, one should not overlook the potentially key role that these countries (i.e. as new players in the renewables area) could play in terms of both addressing climate change and achieving a sustainable future for the world as a whole.

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