Winds of change: expanding renewable energies in developing countries

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Winds of Change

Expanding renewable energies in developing countries:

Towards a better understanding of the determinants of
technological transitions

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Winds of Change

Expanding renewable energies in developing countries:

Towards a better understanding of the determinants of
technological transitions

DISSERTATION

to obtain the degree of Doctor at Maastricht University,
on the authority of the Rector Magnificus, Prof. Dr. Rianne M. Letschert
in accordance with the decision of the Board of Deans,
to be defended in public on
Tuesday 19 December 2017, at 13.30 hours

by

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Prof. Dr. Rainer Walz, Fraunhofer ISI

Dr. Rasmus Lema, Aalborg University

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Abstract

A fossil fuel dominated consumption of energy has contributed to a 35% increase of global net greenhouse gas emissions in just two decades (1990-2010) (46 billion metric tons of CO₂e). The increasing concentration of greenhouse gases has led to warming between 0.5 °C and 1.3 °C of the global mean surface temperature over the period 1951 and 2010.

This thesis addresses one of the major challenges to combat climate change, namely that of reducing greenhouse gases in the energy sector. It does so through an analysis of the blocking and driving mechanisms of technological transitions towards renewable sources of energy. The thesis places a specific focus on the adoption of renewable energy technologies in developing countries, using Colombia as an example. In order to analyze the barriers and drivers of technological change, the thesis uses the Technological Innovation System (TIS) approach, and complements it by explicitly assessing the influence of socio-economic and political factors in technological transitions.

The empirical analysis of barriers and drivers for wind energy in Colombia shows that the country has a high potential for wind energy development, but the reliance on hydropower, backed-up by thermoelectric power has created a sense of a stable and clean energy mix, which is becoming a barrier to transitioning towards other alternative sources of energy. Additional factors obstructing the transition include corruption, unequal access to education and the armed conflict. On the other hand, increasing climate variability is putting pressure on actors within the incumbent energy system to break out of the current hydro-thermoelectric lock-in and to diversify to other RETs.

The thesis shows that by explicitly and systematically including additional socio-economic and political factors to complement the TIS analysis, comprehensiveness improves, while revealing additional avenues for medium and long-term policies to expand RETs adoption in developing countries. In addition, the evidence suggests that a reconsideration of the boundary of the technological innovation system approach is necessary in developing countries, as an additional set of socio-economic and political factor appear to influence technological transitions more than in high-income countries.

In addition, the research examined in more detail if one of the factors with potential to facilitate RETs transitions, namely environmental and RETs awareness, can be strengthened through environmental education. The results demonstrated that environmental education is a necessary but not sufficient condition to raise awareness in the case of Colombia.

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List of Acronyms

ACOLGEN	Asociación Colombiana de Generadores de Energía Eléctrica (Association for Colombian Energy Generating Companies)
AIC	Akaike Information Criteria
ANDEG	Asociación Nacional de Empresas Generadoras (National Association for Generating Companies)
BIC	Bayesian Information Criteria
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CND	Consejo Nacional de Discapacidad (National Dispatch Center)
CNO	Consejo Nacional de Operación (National Council of Operation)
CO ₂ e	Carbon Dioxide Equivalent
COLCIENCIAS	Departamento Administrativo en Colombia de Ciencia, Tecnología e Innovación (Colombian Association for Science, Technology and Innovation)
CREG	Comisión de Regulación de Energía y Gas (Regulatory Commission for Energy and Gas)
DNP	Departamento Nacional de Planeación (Department for National Planning)
EA	Environmental Awareness
EE	Environmental Education
EGC	Energy Generating Companies
EIA	U.S. Energy Information Administration
ENSO	El Niño Southern Oscillation
EPA	Economic Partnership Agreement
ESCS	Economic, Social and Cultural Status
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEM	Global Entrepreneurship Monitor
GHG	Greenhouse gases
GMO	Genetically Modified Organisms
GNI	Gross National Income
GWEC	Global Wind Energy Council
IDB	Inter-American Development Bank
IEA	International Energy Agency
ILO	International Labour Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISCED	International Standard Classification of Education
MLP	Multiple-Level Perspective
MME	Ministerio de Minas y Energía (Ministry of Mines and Energy)

NAMA	Nationally Appropriate Mitigation Actions
NGO	Non-Governmental Organization
NIS	National Innovation System
OECD	Organisation for Economic Co-operation and Development
Oxfam	Oxford Committee for Famine Relief
PACES	Programa de Ampliacion de Cobertura de la Educacion Secundaria
PISA	Programme for International Student Assessment
PPP	Purchasing Power Parity
R&D	Research & Development
REN21	Renewable Energy Policy Network for the 21st Century
RET	Renewable Energy Technology
RIS	Regional Innovation System
SES	Socio-Ecological System
SI	Systems of Innovation
SIN	Sistema Interconectado Nacional (National Interconnected System)
SIPRI	Stockholm International Peace Research Institute
SIS	Sectoral Innovation System
SSPD	Superintendencia de Servicios Públicos (Superintendent of Public Services)
TIS	Technological Innovation System
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UPME	Unidad de Planeación Minero Energética (Planning Office for Mining and Energy)
VAT	Value Added Tax
WLE	Weighted Likelihood Estimation
XM	Compañía de Expertos en Mercados (Public Service Company)
ZNI	Zonas No Interconectadas (Non-Interconnected Zones)

Glossary of Key Terms

<i>Activities (of the innovation system)</i>	Activities refers to the same aspects as functions, namely the integral processes an innovation system.
<i>Carbon Dioxide Equivalent</i>	Term used to describe different greenhouse gases with a common unit. Any quantity of a greenhouse gas is calculated using its individual Global Warming Potential (GWP) and expressed in CO ₂ (e.g., since methane has a 25 times higher GWP than CO ₂ , 1 kg of methane would be equal 25 kg CO ₂ e).
<i>El Niño</i>	The warm phase of El Niño Southern Oscillation (ENSO) phenomenon produces less than average precipitation and prolonged dry seasons, leading to droughts.
<i>Endogenous</i>	Factors referred to as being 'inside' or part of the system.
<i>Exogenous</i>	Factors referred to as being 'outside' or not part of the system.
<i>External Factors</i>	Refer to aspects that are not considered to be integral internal factors to the formation of a specific technical innovation process (e.g. organizations and individuals directly contributing with specific knowledge, technical skills and resources), but that may assert influence on the TIS.
<i>Feedback Loops (Positive or Negative)</i>	Feedback loops result from linkages between the actors. They may have positive or negative effects in response to interventions, such as change of policy, and they are the reason the response to an intervention is non-linear.
<i>Focal System/Focal TIS system</i>	Refers to the collection of the most central elements, activities and linkages (systematic interdependencies) necessary for the system to achieve its purpose.
<i>Framework Conditions</i>	Refers to factors that make up the wider context in which firms innovate.
<i>Functions</i>	Refers to processes integral to the creation and development of a technical innovation system and supports a systemic analysis that can help to identify characteristics of the system, such as weaknesses and strengths.
<i>Jepirachi</i>	Name of the first Colombian Wind Energy Park.
<i>La Niña</i>	The cold phase of ENSO in turn is manifested through higher than average precipitation and prolonged wet seasons, often leading to floods.
<i>Landscape Factors</i>	Landscape factors or Socio-Technical Landscape Factors originates from the Multiple-Level Perspective framework and refers to macro-level factors with the potential of influencing existing actors involved in the technology in questions and provide opportunities for new technologies to emerge.
<i>Multiple-Level</i>	The MLP framework includes three levels, where the socio-

<i>Perspective</i>	technical landscape level refers to macro level factors. The other levels are the <i>niche</i> (micro - protected spaces for emerging innovations) and <i>socio-technical regime</i> (meso – incumbent technical systems).
<i>Non-linear</i>	This refers to the response of a system to an intervention. A linear intervention may not result in a linear outcome.
<i>System Boundary</i>	Where the system ends and the remaining world continues.
<i>Technological Transition/Socio-Technical Transition</i>	These terms refer to how technological innovations develop and become part of the society, i.e., not restricted to technological aspects of transition. In this thesis the two terms are used interchangeably.
<i>Wider Context</i>	Refers to a collection of factors considered to be outside of the focal system (see focal system).

Chapter 1. Introducing the Rationale and the Focus of the Research

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development 1987).

1.1 Recognizing the wider Sustainability Challenge

There is scientific evidence that human influence on the resources necessary to support life on Earth has reached unparalleled levels (IPCC 2014; Jerneck et al. 2011; Millennium Ecosystem Assessment 2005; Steffen et al. 2015). Since the mid-1980s, human consumption of natural resources has resulted in an ‘ecological debt’ of borrowing from Earth’s biological capacity from future generations. Roughly 1.5 planets are required to provide the resources for the current human consumption (Global Footprint Network 2015). An increasing world population combined with a rapidly rising material and per capita energy consumption is exacerbating the ecological deficit.

Human influence on the planet includes pollution of oceans, reduced freshwater availability, and loss of biological diversity. In a 2009 study by Rockström et al., a framework was introduced that identified nine ‘Earth System processes’ (or planetary boundaries) argued to be essential for sustained human development on the planet. The planetary boundary processes include climate change, depletion of stratospheric ozone, land use change, freshwater use, rate of loss of biological diversity, ocean acidification, nitrogen and phosphorus inputs to the biosphere and oceans, air pollution from aerosol loading and chemical pollution. In the most recent update of the framework by Steffen et al. (2015), four out of nine of the Earth processes have surpassed their sustainable boundaries. The four processes are loss of biosphere integrity, land-system change, altered biogeochemical cycles (phosphorus and nitrogen) and climate change (Steffen et al. 2015). Oxfam extended the planetary boundary idea by incorporating social aspects, emphasizing the interdependence between environmental sustainability and social and economic development (Raworth 2012).

This thesis addresses one of the major sustainability challenges; that of climate change, through an analysis of blocking and driving determinants of technological transition, including the influence of socio-economic and political factors. The thesis places a specific focus on the adoption of renewable energy technologies in developing countries, using Colombia as an example.

1.1.1 Climate Change

Emissions of anthropogenic greenhouse gases (GHG) have increased significantly since the industrial revolution. About 40% of the emissions between 1750 and 2011 have remained in the atmosphere, increasing the concentrations of carbon dioxide, methane and nitrous oxide. Land and oceans have absorbed the rest of the emissions (IPCC 2013). It has been estimated that global net greenhouse gas emissions¹ in 2010 amounted to almost 46 billion metric tons of CO₂ equivalent (CO₂e), a 35% increase from 1990. Energy production and use (including emissions from fuels from vehicles) represented about 71% of the global greenhouse gas emissions for that year (EPA 2016). The increasing concentrations of greenhouse gases have led to warming between 0.5 °C and 1.3 °C of the global mean surface temperature over the period between 1951 and 2010 (IPCC 2013).

These changes to the Earth's energy balance and the resulting change in climate have led to an intensification of flooding in some parts of the worlds and extreme heat waves and drought in other parts, all of which have a significant impact on human development (IPCC 2012). Moreover, according to leading scientists, with the current commitments as outlined in the United Nations Framework Convention on Climate Change (UNFCCC), global temperature is still expected to increase between 3.5-4.0 degree Celsius during the 21st century, with detrimental human and planetary effects (The World Bank 2012a). In an effort to avoid this, in December of 2015, 195 countries agreed to a global action plan with the objective to keep the global warming below 2.0 degrees Celsius (European Commission 2016).

The Paris agreement (United Nations 2015) represents an equally positive and pressing ambition for tackling climate change. Projections made up to 2040 show that energy use is expected to grow substantially, however predominately in non-OECD countries (>85% of the increase), as a result of population increase, economic growth and, higher standard of living (EIA 2013). Meeting the goals of reduced emissions will require a rapid and successful expansion of a wide range of mitigation alternatives.

1.2 Mitigation Strategies

The reduction of green house gas emission would require a multifaceted approach involving a wide spectrum of strategies, such as alternative energies, negative emissions (e.g., carbon capture), or demand side management (e.g., energy efficiency and behavioral change). From the demand side management, addressing

¹ Net emissions include the effects of land use and forestry.

human consumption and behavior, alongside the transitions towards alternative energy sources has been emphasized as an essential aspect of mitigation strategies (Victor et al. 2014). In fact, the risk of losing important energy efficiency gains to increased human consumption has long been emphasized by the work on the rebound effect (Binswanger 2001; Greening and Greene 1998).²

1.2.1 The Role and State of Renewable Energy Technologies

Renewable energies technologies (RETs) are widely acknowledged as one of the most important aspects of climate change mitigation (IPCC 2012).³ Beyond the positive environmental implications, given the low operation and maintenance costs, RETs could also be considered a principal instrument in alleviating energy poverty in developing countries (Bhide and Monroy 2011).⁴ RETs have also been attributed with the potential to improve energy security for the future (ADB 2009). Moreover, by diversifying its energy mix, countries can avoid increasing costs and price volatility of fossil fuels, which can hamper economic growth and result in exacerbating effects on poverty alleviation in many regions (IEA 2011; Victor et al. 2014).⁵

Despite the apparent recognition for the importance of transitioning to renewable energy sources, the total share of global electricity generated from renewable sources has decreased. In fact, in 1990, renewable sources represented 19.5% of the global electricity generation, and in 2009, this share fell to 19.3%, largely due to that growth in demand has been predominately supplied by conventional technologies (EIA 2013).⁶ Moreover, after three decades of encouraging the transition to RETs, it is estimated that only 20-25% of their full potential has been

² A broad definition of the rebound effect can be described as when the growth of an economy overcompensates the increases in efficiency gained by technological innovation (Radermacher 1997).

³ It should be noted that RETs are not problem free, e.g., food security and high GHG emission during the lifecycle of certain biofuels (Delucchi 2010).

⁴ Approximately 1.2 billion people are without access to any form of electricity and without successful policy interventions, 1 billion people are still expected to be without electricity in 2030 (IEA 2015). Worst off is Sub-Saharan Africa, with data from 2014 demonstrating that only 35% of the population has access to electricity, with as little as 19% in rural areas (IEA 2016b).

⁵ See also e.g., *The Economics of Climate Change: The Stern Review*, written by Nicholas Stern (2007).

⁶ It should be noted that from the sustainability perspective renewable sources vary significantly in terms of impact on the environment. An example of this is the Niagara Falls (US) vs. the Three Gorges project (China), both being examples of hydropower, but the latter having a considerable negative human and ecological impact.

achieved (Rao and Kishore 2010). According to the International Energy Agency, by 2020 a doubling of today's level of energy generated by renewable sources is necessary, in order to achieve the objective to cut global GHG emissions by half by 2050 (IEA 2011). Motivated by the pertinence of increasing the share of RETs in the energy supply of countries, understanding the mechanisms that hinder a more rapid transition towards RETs represent a key aspect of sustainability research.

1.3 Identifying Blocking Mechanisms to Energy Transition

To enable policy makers to take the appropriate actions that facilitate the transition towards new technologies, such as renewable energies, an improved understanding of the mechanisms that hinder or drive a rapid diffusion is needed. Such research includes identifying determinants that may exist in a number of actors such as firms, government organizations, knowledge generating organizations such as universities, the general public through norms and attitudes, or in the quality of institutions. Moreover, the barriers to transition towards RETs may exist between rather than simply within, in the form of insufficient links or communication between the various actor groups (Edquist 2001). This complexity is further exacerbated when considering that the 'right' or adequate set-up for technical transitions differs between nation states.

Identifying determinants of technological transitions should be based on two fundamental principles. The first is an interdisciplinary approach that encompasses the potential determinants across different actors groups, and considers social, economic, political and environmental factors, and thus transcends academic disciplines. Limiting the analysis of technological transitions to economic and technological aspects would significantly reduce comprehensiveness, and the possibility for designing well-targeted policies. The second is a clear structure that allows for a systematic analysis of potential determinants, due to the complexity of factors and actors that influence technological transitions. A combination of a holistic and reductionist reasoning would be required to allow for potential determinants from a wider perspective to be considered, while keeping the analysis to manageable scale that permit for well-measured policy suggestions to be devised and implemented.

1.3.1 A Systems Approach

One framework where an interdisciplinary and systematic analysis of multiple factors is possible is through a systems approach. Early protagonists argued for a holistic approach, in order to encompass the complex and evolutionary

characteristics of living beings or society (Weckowicz 2000).⁷ The systems approach is usually required to “break down the boundaries between academic disciplines” (Forrester 2009, 9), fulfilling the interdisciplinary requirement of utilizing a systems approach for studying technological transition. A holistic approach of system thinking can also be found in the systems of innovation literature, where Charles Edquist (1997, 14) defines a system as being “all important economic, social, political, organizational, institutional, and other factors that influence the development, and use of innovation”.

1.3.2 Delimiting a Complex System

In order to empirically analyze a system it is imperative to know what factors are part of the system and what factors should be left out. In other words, a system under study must be delimited from the rest of world in order for a boundary to be established.

A manner of delimiting the boundary of the system under study, other than spatially (e.g., borders of nation) or by sector (e.g., specific technological field) is to ‘simply’ identify the activities or determinants that influence the development and utilization of an innovation (Edquist 2005). Delimiting a system of innovation by identifying all of its determinants may not be possible. However, identifying as many relevant determinants as possible can serve as a guiding objective, which in turn can incrementally improve the accuracy of delimiting the system while enhancing the comprehensiveness of the systems of innovation approach.

One example of an attempt to delimit a system, both by sectoral delimitation and by determinants is through the Technological Innovation System (TIS) approach and its lists of functions.⁸ These lists of functions, developed by several authors in the TIS literature, specify the integral processes believed to be necessary to create, develop and utilize a ‘new’ technology. They provide a concrete set of functions that can be utilized as a framework for empirical analysis can help translate empirical findings into usable policy suggestions.

The potential risk when delimiting the system is that important determinants of the innovation system under study are left out of the analysis. In fact, several authors have criticized the TIS approach for being too *inward looking* and ignoring the

⁷ Ludwig von Bertalanffy, an Austrian biologist, argued for an open ‘holistic’ systems approach already in the 1930s. While beginning his work in the areas of physics and biology, he would broaden his approach to create a General Systems Theory with application in social sciences (Weckowicz 2000).

⁸ See for example Johnson and Jacobsson (2001) and Bergek et al. (2008).

aspects that would be described as exogenous to the TIS system (Coenen and Díaz López 2010; Markard and Truffer 2008). The other limitation arises when the TIS approach is applied in a developing country context. The approach has been developed for and mainly tested in high-income countries, such as the Netherlands, Germany and Sweden (S. Jacobsson and Bergek 2004; Negro, Hekkert, and Smits 2007; Negro, Suurs, and Hekkert 2008). However, the application of the TIS approach in a developing country context is emerging.⁹ As shown throughout the chapters of this thesis, understanding technological transitions in developing countries requires complementing the list of endogenous and ‘exogenous’ factors of the system.

1.3.3 Social and Political Factors – Endogenous or Exogenous to the System?

Addressing the criticism of the TIS approach for not sufficiently taking into consideration its wider context¹⁰, and adjusting the framework to developing country contexts, may require a re-thinking of the boundaries for the technological system. Aspects that have previously been overlooked and considered external to the focal TIS system could instead be considered endogenous to the system, if regarded as determinants (positive or negative) for innovation. While the objective is not to include all socio-economic factors as part of the Systems of Innovation several questions remain. Which factors do exercise an influence on the integral elements of the systems of innovation that should not be ignored? How does this potential influence differ in countries of different income-level¹¹, e.g., developing (low, low-middle, upper-middle) and developed (high-income) countries?

Another framework that has developed parallel to the systems of innovation approaches is the Multiple-Level Perspective (MLP). The MLP framework has emphasized wider socio-economic and political factors as part of their socio-

⁹ Some examples are Jacobsson and Bergek (2006) (RET specific); Iizuka and Gebreeyesus (2012; 2016) (Agriculture Sector).

¹⁰ Throughout the chapters of this thesis, the terminology *wider context* and *framework conditions* are both used to describe factors that are generally not considered part of the inner workings of the technological innovation system, but that may still exercise influence on technological transitions.

¹¹ This thesis uses the income classification (GNI per capita) by the World Bank. For the fiscal year of 2017, low-income economies are those of \$1,025 or less; lower middle-income economies (\$1,026 to \$4,035); upper middle-income economies (\$4,036 to \$12,475); and high-income economies have a GNI per capita of \$12,476 or more. Low, lower middle and upper middle-income are characterized as developing countries (The World Bank 2016b).

technical landscape analysis.¹² Leading authors have raised factors such as “oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems” (Geels 2002, 1260). Other authors refer to the importance of environmental awareness in socio-technical transitions. They declare that “growing environmental awareness is a socio-cultural development that can be considered a landscape process, and which is questioning the performance of multiple regimes, whilst generating opportunities for niches” (Smith, Voß, and Grin 2010, 441). Other disciplines, e.g., psychology research, have also demonstrated a link between environmental awareness and a higher preference for energy produced from RETs (see e.g., De Groot et al. 2012; Steg, Dreijerink, and Abrahamse 2005; Van der Werff, Steg, and Keizer 2013). Moreover, in developing countries, studies that specifically analyzed the awareness about RETs found a lack of awareness concerning the new technologies to constitute a significant barrier for its adoption (Reddy and Painuly 2004; Kennedy and Basu 2013; Luthra et al. 2015). Other frameworks and previous interdisciplinary research can assist in identifying sociopolitical factors that should be considered when assessing the determinants and consequently the boundaries for systems of innovation.

Again, identifying all the determinants that drive or block technological innovation may not be possible, especially since the evolutionary nature of socio-technical systems signify that the systems change over time. In this thesis, the preferred approach to systems of innovation and technological transition is that of Lundvall (1992) who argues for a flexible approach to deciding what processes to consider in a system.

1.4 Aim and Scope of Thesis

This introductory chapter has identified the need to expand the adoption of RETs, predominately motivated by climate change, but to reduce energy insecurity and energy poverty. Several conceptual weaknesses and remaining challenges in current approaches to systematically analyze the barriers and drivers to RETs adoption have been raised along with the need for additional empirical analyses, particularly in developing countries.

Inspired by these challenges and research gaps, the thesis aims to contribute to the understanding of the mechanisms that hinder or drive adoption of RETs, with a special focus on developing countries. This compilation thesis is made up of four

¹² The MLP framework includes three levels, where the socio-technical landscape level refers to macro level factors. The other levels are the *niche* (micro - protected spaces for emerging innovations) and *socio-technical regime* (meso – incumbent technical systems).

substantive Chapters (Ch. 3-6), which address related research questions and a wide range of possible determinants of energy transition, through an interdisciplinary lens. The chapters vary in their level of analysis, from a wide approach where multiple possible determinants are included in the analysis (Chapters 3, 4 and 6), to zooming into a specific determinant (Chapter 5).

The substantive Chapters (Ch. 3-6) are preceded by a literature review in Chapter 2. The literature review brings together the background literature and identifies gaps that need to be addressed to advance the subject. These research gaps presented in Chapter 2 have motivated the work described in the subsequent chapters. In Chapters 3-6, there is some repetition of what is found in Chapter 2. This is deliberate as it allows each of the Chapters (Ch. 3-6) to stand alone. Finally, Chapter 7 concludes the thesis by revisiting key findings and discussing how these can translate into feasible policy suggestions. Chapter 7 finishes by elaborating on remaining challenges not addressed in this thesis. They lead to recommendations for future research.

1.4.1 TIS and the Wider Context: A framework for developing countries

The first substantive Chapter (Ch. 3) begins by addressing limitations raised by previous scholars concerning the TIS function approach. In order to conceptually map integral elements and activities along with wider contextual factors of technological transitions in a developing country context, Chapter 3 undertakes a thorough review of previous approaches (TIS and MLP), along with additional cross-disciplinary research. The chapter proposes an analytical framework that includes additions to the list of integral processes or functions of the TIS, along with wider contextual factors that may influence the system. This framework sets the stage for two empirical studies (Chapters 4 and 5), and one conceptual chapter (Chapter 6).

1.4.2 Empirical Studies

While Chapter 3 theoretically justifies the inclusion of the factors that make up the framework used in this thesis, Chapter 4 empirically tests the framework in a case study analyzing barriers and drivers to wind energy adoption in Colombia. Next, Chapter 5 zooms into one of the contextual factors discussed in Chapter 3 and 4, namely environmental awareness, by performing an empirical study on the effectiveness of environmental education in creating environmental awareness in 15-year old adolescents in Colombia.

1.4.3 Rethinking System Boundaries

Chapter 6 builds on the knowledge acquired in the first three related Chapters (3, 4 and 5), dedicated to advancing the knowledge on the contextual factors/framework

conditions. The chapter elaborates on the contextual factors deemed exogenous by the TIS literature, through theoretical discussion, combined with empirical evidence from previous case studies of countries from different income-levels. By using a wider Systems of Innovation (SI) approach to map framework conditions, Chapter 6 addresses the issue of systems boundaries, i.e., should these framework conditions be considered endogenous or exogenous of the system. Moreover, by including countries of different income-levels, Chapter 6 attempts to differentiate the role of framework conditions between developing and developed countries, and the conceptual consequence this may have for delimiting the system.

1.4.4 Lessons Learned and Next Steps

In the last Chapter (Ch. 7), the conceptual and empirical findings from Chapters 3-6 are revisited and reflected upon. The final Chapter collates the findings presented in this thesis in an effort to emphasize specific contributions from the individual chapters, but also how they relate and reinforce each other. Moreover, Chapter 7 dedicates a session for discussing how the findings, including driving and obstructing framework conditions, found in this thesis could be translated into short/medium-term and long-term policy suggestions. Finally, this chapter concludes by highlighting remaining challenges and suggests possible avenues for future research.

Chapter 2. Background Literature & Research Gaps

In this thesis, a specific focus is placed on attempting to understand and improve strategies for accelerating the transition towards sustainable energy alternatives, namely Renewable Energy Technologies (RETs). As discussed in the previous chapter, increasing the share of RETs in a country's energy mix can contribute to energy security and climate change mitigation. As highlighted in Chapter 1, enhancing the understanding concerning the mechanisms that hinder or drive a rapid diffusion of RETs requires an interdisciplinary approach capable of identifying potential determinants across different actor groups in a systematic and structured manner.

Over the past decades, a multitude of theoretical approaches to analyze sustainable technological transitions have emerged, such as *social construction of technology* (Bijker, Hughes, and Pinch 2012), *sociology of expectations* (Van Lente and Rip 1998; Borup et al. 2006), *constructive technology assessment* (Rip, Schot, and Misa 1995), *technology future studies* (Porter et al. 2004; Truffer, Voß, and Konrad 2008), *reflexive governance* (Kuhlmann, Shapira, and Smits 2010; Voß, Bauknecht, and Kemp 2006), *long waves* (Freeman and Louçã 2001; Perez 2002), *Transition Management* (Kern and Smith 2008; Loorbach 2010; Rotmans, Kemp, and Van Asselt 2001), *Strategic Niche Management* (Kemp, Schot, and Hoogma 1998; Raven and Geels 2010; Smith 2007), *Multiple-Level Perspective* (Geels 2002; Geels and Schot 2007; Smith, Voß, and Grin 2010), *Technological Innovation System* approach (Bergek et al. 2008; S. Jacobsson and Johnson 2000; Hekkert et al. 2007), and *Systems of Innovation* approach (Edquist 1997).

A theoretical discussion about all the possible approaches for studying sustainable transitions is beyond the scope of this thesis. The literature review will therefore be restricted to the approaches used in this thesis, namely Technological Innovation System (TIS), Multiple-Level Perspective (MLP) and Systems of Innovation (SI). The TIS, MLP and SI have been selected as theoretical framework because they stand out from other approaches in that they support a comprehensive analysis of a wide array of socio-technical aspects in a systematic manner. Given the focus of this thesis on identifying barriers and driving mechanisms for expanding RETs adoption, these wide-ranging frameworks provide a good conceptual starting point.

This chapter will review essential background literature of the theoretical frameworks used in this thesis. The chapter will also highlight the existing limitations of these frameworks, motivating the focus and theoretical contributions, which will be made in Chapters 3-6. As the literature reviewed in this chapter will show, questions remain about what factors should be considered when applying a systems approach, especially in a developing country context. This thesis aims to

shed light to these questions through the conceptual and empirical analyses done in Chapters 3-6.

Since both the TIS and SI framework are grounded on systems approaches, the literature review will begin by providing a review of the systems literature. Following, the systems of innovation approaches will be presented, including the TIS, its advantages and limitations. This leads to a discussion about defining the boundary of the system in question, in the case of this thesis, renewable energy technological innovation systems. Next, the MLP approach will be introduced. In this thesis, the MLP serves as a complement to the TIS, in order to consider potentially influential factors not explicitly encapsulated by previous TIS studies and to make the framework better suited for analyses in developing countries. Due to discrepancies regarding the use of various terms in previous literature, this chapter will also provide definitions of key concepts used throughout this thesis such as *innovation, institutions, and organizations*.

2.1 Systems

2.1.1 Early Developments and Use of Systems

A systems approach for analyzing complex phenomena has for long been used in natural science, where in certain conditions, i.e., when the exact number of particles or elements in the system is known, a closed system analysis can be applied. However, the complexity and possibility of external influences in socio-technical transitions does not allow for a closed system. The rationale for an open systems approach was argued for already in the 1930s by the Austrian biologist Ludwig von Bertalanffy.¹³ While von Bertalanffy began his open system discussion in the area of physics and biology (Bertalanffy 1950b), he would extend his theory to create a General Systems Theory (Bertalanffy 1950a), which would transcend natural sciences to also prove applicable in social science (Weckowicz 2000). The central argument by von Bertalanffy, sprang from a description of living things as an evolutionary, dynamic and complex system, a complexity¹⁴ that could not be justified by the previously held mechanistic perspective, which explained life by the laws of physics and chemistry (Weckowicz 2000). Just as in the case of a biological organism, he contended that a reductionist view was

¹³ His original publications on the open systems theory were written in German in 1932 and 1942. A publication followed in English in 1950, titled: The Theory of open systems in physics and biology.

¹⁴ The word complex has its origin in the latin word *plectere*, meaning entwine or to weave. Complexity of a system can be described as immensely entwined simple parts. For a detailed discussion about complexity or complex systems, see Mitchell (2009).

inadequate to explain complex intricacies of societies, but instead argued for a holistic systems approach.

An elaboration about the dynamic and complex nature of systems was initiated by Jay Forrester in the 1950s, which would culminate in several important publications in the 1960s and onwards.¹⁵ This approach, which became known as *system dynamics*, placed a special emphasis on the relationship or links between different components of the system. These links between the elements of the system provided positive or negative *feedback loops*. A consequence of the feedback loops was that interventions to change the behavior of the system resulted in non-linear outcomes. These dynamic and non-linear characteristics contribute to a higher degree of complexity of the system. While systems dynamics began with a focus on industrial dynamics, the breadth of the approach has been expanded and used in areas such as, urban system (Forrester 1969), social-ecological systems (Ostrom 2009) and even global systems.¹⁶

2.1.2 Key Components of Systems

A system can in general terms be described as “any group of interacting, interrelated, or interdependent parts that form a complex and unified whole that has a specific purpose” (Kim 1999, 2). The links or interdependencies between parts or components, in the form of positive or negative feedback loops is what makes it a system, rather than a collection of different parts. In fact, in Forrester’s system dynamics, the relationships between the different elements are considered as vital to the configuration and behavior of any system as the actual elements (Meadows et al. 1972). In addition, understanding the boundary of the system under study, i.e., where the system ends and where the remaining world continues, is essential for empirical studies to be undertaken (Edquist 2005).

2.2 Using Systems Thinking for Studying Innovation

The study of innovations has increasingly seen the use of systems approaches as such approaches allow analyzing the complexity, nonlinearity and feedback loops of different types of innovations, such as technological, organizational and marketing. This section will begin by defining innovation, followed by an introduction of different Systems of Innovation Approaches before discussing in detail the Technology Innovation Systems Approach (TIS).

¹⁵ See for example, Forrester (1961; 1968)

¹⁶ System Dynamics modeling was used for The Limits to Growth publication (Meadows et al. 1972).

The Meaning of Innovation

The term innovation is used extensively, but with varying meanings (Edison, bin Ali, and Torkar 2013). While discussing all the different definitions of innovation is beyond the scope of this chapter, it is important to review a few distinctions in order to establish the concept of innovation and how it relates to the Systems of Innovation framework that is used in this thesis.

One of the most ambitious efforts of defining innovation has been undertaken by the OECD and Eurostat, in the form of the Oslo Manual, which was first published in 1992 (OECD 1992). An important ambition of the Oslo Manual was to improve the measurement of firms' propensity to innovate and track it over time. Following the first edition of the Oslo Manual, which focused on manufacturing, while including technological product and process innovation, the definition of innovation has evolved, resulting in second and third editions of the manual. In paragraphs 146 and 150 of the third edition the definition of innovation is described as follows:

146. An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations.

150. A common feature of an innovation is that it must have been implemented. A new or improved product is implemented when it is introduced on the market. New processes, marketing methods or organisational methods are implemented when they are brought into actual use in the firm's operations (OECD/Eurostat 2005, 46–47).

As can be inferred from paragraph 146 and 150, in order for e.g., a product to be considered an innovation, it must be *new* or *significantly improved* and *introduced to the market*. If it is not introduced on the market it is not considered an innovation but rather an invention (Gault 2016). With regard to the concept of *novelty*, the manual includes several degrees of novelty, including “new to the firm, new to the market, and new to the world” (OECD/Eurostat 2005, 57). “The minimum entry level for an innovation is that it must be *new to the firm*” (OECD/Eurostat 2005, 57). In other words, “an innovation does not need to be developed by the firm itself but can be acquired from other firms or institutions

through the process of diffusion¹⁷” (OECD/Eurostat 2005, 17). By including this minimum degree of novelty, the Oslo Manual allows for the concept of *adoption* of e.g., a technology, between firms or even between countries, through the process of diffusion.

This broad degree of novelty provided by the Oslo Manual has strong similarity to certain definitions by early system of innovation thinkers. For example, Nelson and Rosenberg (1993, 4–5), define innovation “rather broadly, to encompass the processes by which firms master and get into practice product design and manufacturing process that are new to them, whether or not they are new to the universe, or even to the nation”. As stated by Edquist (1997), their concept of innovation is not limited to its first introduction but also include its diffusion, e.g., the adoption of a technology that is new to the firm or the country.

As discussed in Chapter 1 as well as in the introduction of this chapter, a main focus of this thesis is the diffusion of sustainable energy alternatives, namely Renewable Energy Technologies (RETs). In Chapter 4, an empirical study is undertaken in Colombia to understand the slow adoption of wind energy. Wind energy in Colombia was first implemented (introduced on the market) in 2003 but has since been stagnant. The technology is relatively new to the country as well as most firms in Colombia. These two conditions, i.e., that wind energy is new to most firms and has been introduced to the market satisfies the required definition of innovation as stipulated by the Oslo Manual. That said, since the thesis is concerned with RETs and with special focus on wind energy in Colombia, the definition of innovation would be imposed with a restriction (Gault 2016). The restriction of focusing on a specific technology will have implications for measuring and ultimately for policies (Gault 2016), as data gathering and analysis would focus on the technologies in question. Details about how data is gathered for the restricted innovation, including the structured and semi-structured interviews conducted for the qualitative data collection and analysis will be discussed in Chapter 4 and shown in Appendix I (final interview guide).

Furthermore, the research conducted in this thesis is not solely interested in the propensity of firms to innovate but rather to explain what hinders and drives adoption of RETs. In other words, this thesis is interested in the processes that block or enable the adoption of technological innovations, which requires a wider perspective beyond firms. In the words of Jan Fagerberg (2005, 20), “a firm does not innovate in isolation, but depends on extensive interaction with its

¹⁷ The Oslo Manual describes diffusion as “the way in which innovations spread, through market or non-market channels, from their very first implementation to different consumers, countries, regions, sectors, markets and firms” (OECD/Eurostat 2005, 17).

environment”. This environment is made up by a wide array of “other firms (suppliers, costumers, competitors etc.) or non-firm entities such as universities, schools, and government ministries”, whose behaviors are “shaped by institutions- such as laws, rules, norms and routines” (Edquist 2005, 183), all of which may influence innovation. Put differently, “innovation is constrained or advanced by the cultural, geographical, and legislative and regulatory environment in which it happens” (Gault 2010, 104). Consequently, understanding a slow adoption of RETs thus requires a framework that encapsulates the myriad of potential determinants that may have a positive or negative influence on diffusion. By taking a systems approach to study innovation, this thesis aims to contribute to the understanding of the multiple processes influencing innovation, beyond, but not excluding, firms. The next section will review the systems of innovation approaches, including their advantages, remaining limitations and research gaps. Chapter 3 discusses in greater detail the framework that is used to measure key processes of the innovation system, again with restrictions imposed by its focus on RETs.

2.2.1 Systems of Innovation (SI) Approaches

Various Systems of Innovation (SI) approaches have been developed since the mid-1980s as analytical frameworks and policy tools. There are some approaches with a geographical focus such as the National Innovation System (NIS) (Freeman 1987; Lundvall 1992; Nelson 1993), and the Regional Innovation System (RIS) (Cooke, Uranga, and Etzebarria 1997; Saxenian 1994); the Sectoral Innovation System (SIS) (Breschi and Malerba 1997) focuses on an industrial sector; the Technological Innovation System (TIS) (Carlsson and Stankiewicz 1991), in turn, focuses the analysis on a technology. While they are distinct approaches, they are also interrelated as a specific technology innovation system, for example, can operate at the national, regional and/or sectoral level (Markard and Truffer 2008).

The National Innovation Systems (NIS) approach is the most common SI approach. NIS was first used by Freeman (1987) in an analysis of Japan’s economic and technological policy and development. He defined the NIS as “the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies” (Freeman 1987, 1). Lundvall (1992, 13), who has also developed and used the NIS approach, defines it as “all parts and aspects of the economic structure and the institutional set up affecting learning as well as searching and exploring”. Different authors diverge somewhat in the definition of an NIS, however the central elements remain the same.

The Technological Innovation System (TIS) approach has been defined as “a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization

of technology” (Carlsson and Stankiewicz 1991, 94). The NIS and TIS share the focus on technology and the importance of institutions. The TIS approach is, however, different from NIS in that a technology is often not limited to the national border or geographical boundary (Carlsson 1995). Given that a technological sector often transcends national boundaries, strictly using NIS may make technological analyses fall short in analytical scope. That said, focusing too strictly on the technological sector in question also carries risks, i.e., that the analysis becomes too narrow and misses relevant processes that would be captured at the national level. This relates to one of the limitations of the TIS approach that will be discussed in more detail in section 2.3.

2.2.2 Technological Innovation System (TIS)

Actors, Networks, and Institutions make up the fundamental components of the TIS (Carlsson and Stankiewicz 1991). Actors are made up by organizations and individuals who work towards the development of the technology in question (Hellsmark and Jacobsson 2009). Examples of these organizations include research institutes, firms, financial institutions, governmental agencies or policy makers each with specific competences, resources and strategies (Carlsson and Stankiewicz 1991). These actors may be organized in networks where interactive learning (e.g. university-industry networks or user-supplier) and formation of policy networks may occur (S. Jacobsson and Lauber 2006; Bergek, Jacobsson, and Sandén 2008). These actors and networks share a given “sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups” (Edquist and Johnson 1997, 46), known as institutions (North 1991).

Technological innovation systems go through two main stages of development, a formative stage and a growth stage. At the *formative* stage various components necessary for development, diffusion and utilization of the TIS take place, such as knowledge accumulation and configuration of necessary infrastructure and institutional arrangements (Bergek, Jacobsson, and Sandén 2008). During this stage, the system is particularly vulnerable to exogenous influence (Raven 2005). TIS analyses of RETs in developing countries are likely to focus on this stage, and therefore exogenous factors may be particularly important to consider (as will be discussed in Chapters 3, 4 and 6) The length of this stage, which can be decades, depends on the technology in question, market conditions and the actions of industry and policy-making actors (Van de Ven and Garud 1989).

The next stage, the *growth* stage, starts taking place once essential structural components of the TIS have been developed. During this stage, positive feedback loops may occur between components of the system, which can contribute to an acceleration of its development. Negative feedback loops may similarly occur during the growth stage, which may limit or prevent growth. If sufficient positive

feedback loops occurs, the system can then become increasingly self-sustaining, reaching a stable and mature structure capable of withstanding external pressures (Bergek, Jacobsson, and Sandén 2008, 577–78).

TIS Function Approach

To facilitate the analysis of the main processes related to the creation and development of a technological innovation system, system functions were introduced by Johnson and Jacobsson (2001). Functions can be understood as the integral components and activities of the TIS.¹⁸ System functions enable the characterization of the innovation system, its strengths and weaknesses by separately studying its underlying processes (Lundvall et al. 2002; Hekkert et al. 2007). The function approach can also serve to assess the performance of different functions, which can reveal significant information about its drivers and barriers. Furthermore, an ample examination of the functions of the TIS can contribute to a better understanding of the dynamics within the systems, which is a result of the interaction between functions (Johnson and Jacobsson 2001). The lessons drawn from the function analysis can contribute to devising policies for developing, diffusing and adopting a new technology as well as monitoring and evaluating innovation policies.

The TIS function approach has been tested and adjusted by several scholars. As a result, several ‘lists of TIS functions’ exist.¹⁹ Examples of functions that can be included in a TIS analysis include: Entrepreneurial Activities, Knowledge Development, Knowledge Diffusion, Guidance of the Search (expectations set by the government for new technologies), Market Formation, Resource Mobilization, and Creation of Legitimacy (Hekkert et al. 2007). The many sets of system functions that have emerged over the past decade suggest that the TIS function approach is still in a developmental stage and continued improvements will be needed as the understanding of technological innovations advances (Edquist 2005).

Most sets of functions have been developed predominantly in high-income country contexts (Johnson and Jacobsson 2001; Edquist 2005; S. Jacobsson and Bergek 2006; Hekkert et al. 2007), and empirically tested in countries where a technology has achieved a later growth stage (Negro, Hekkert, and Smits 2007; Negro, Suurs, and Hekkert 2008; Negro and Hekkert 2008; Hillman et al. 2008). In fact, several

¹⁸ A parallel from TIS functions can be made to the statistical measurement literature, which refers to the key processes for the development of innovations as *innovation activities* (OECD/Eurostat 2005).

¹⁹ See for example: Bergek et al. (2008); Edquist (2005); Hekkert et al. (2007); Hillman et al. (2008); Jacobsson and Bergek (2006); Johnson and Jacobsson (2001); Suurs and Hekkert (2009).

authors have questioned the applicability of the innovation system approach to developing countries.²⁰ Schott and Wickström Jensen (2008), for instance, argue that without considering the specific context, the innovation system approach cannot be applied to developing countries. This represents a research gap, which will be addressed in Chapter 3. As will be shown in that Chapter, the function analysis in a developing country context is relevant, with an adequate adjustment to the set of functions together with the inclusion of relevant exogenous factors.

2.3 System Boundaries

In the context of technological transitions, the boundary of the system may be regional, national or even global, making the delimiting of the innovation system a persisting challenge. In other words, identifying what should be included in the system and what should be left out remains an important avenue for research, and strategies for defining the boundary of systems differ amongst various authors. Authors such as Lundvall (1992) argue that a flexible approach is to be preferred when deciding what processes to consider in a system.

The system can be delimited by the sector of a technology (e.g., geothermal or wind sector) (Carlsson and Stankiewicz 1991) or in term of its *activities* (Edquist 2005) or *functions*. The concept of focal TIS has been used to refer to a delimited system, which is made up by the functions and their linkages. The focal TIS has also been defined as “the realm where systematic interdependencies in a specific technological field play out” (Bergek et al. 2015, 52). Delimiting the system, however, requires determining which are the relevant innovation activities and the interdependencies that would be encapsulated in the focal TIS (see an example of a list of functions in the previous section). If a narrow boundary is set, there is a risk that relevant interdependencies that fall outside the delimited focal TIS are missed. Edquist (2005, 15) argues that understanding the various activities and their relative importance for any innovation system changes as our knowledge increases.

Furthermore, Charles Edquist (1997, 14) contributes to the delimitation of the system by broadly defining it as “all important economic, social, political, organizational, institutional, and other factors that influence the development, and use of innovation”. Edquist (1997, 15) motivates this broad and comprehensive definition by stating, “an advantage of this definition is that it is open in the sense that it does not *a priori* exclude any determinants. An obvious disadvantage is that it is unspecific at the present state of the art”. Edquist (1997, 15) recognizes the monumental task of identifying all the determinants that make up the innovation

²⁰ See for example: Arocena and Sutz (2000); Schott and Wickström Jensen (2008); van Alphen, Hekkert and van Sark (2008).

system adding that “at the present state of the art, defining the limits of a system of innovation in this way (as all determinants) is a 'catch 22' problem”; he further clarifies “we simply do not know in detail what all the determinants of innovation are, particularly not for all types of innovations” (Edquist 1997, 15).

2.3.1 Categories of Determinants for a Systems of Innovation

Following Edquist’s (1997) suggestion of specifying the boundary of a system based on its determinants (i.e., what helps the system achieve its purpose), a systematic analysis of potential candidates is necessary. Categorizing determinants in a structured manner can also serve as an important tool in the process of identifying what makes up the system, and what is irrelevant for the system to realize its objective. A first step to categorizing the determinants of innovation is differentiating *integral components and activities* from *framework conditions* of the system.

Integral Components and Activities

As previously mentioned, in the TIS literature, integral components and activities are referred to as processes or *functions* of a technological system. Integral components of the system are the ones that shape its formal structures. They include a variety of actors involved in the innovation activities, particularly those related to learning, and include firms, private and public organizations, and universities (e.g. organizations and individuals directly contributing with specific knowledge, technical skills and resources).

The collection of these integral processes or functions is referred to as the *focal system* of technological innovation (or *focal TIS*). Functions within the focal systems are regarded as endogenous to the system. Factors or activities that fall outside the focal system are considered exogenous (Bergek et al. 2015).

Criticisms of TIS

The TIS focus on integral functions has contributed to criticisms of the approach not sufficiently taking into account the influence of external factors to understand technological transitions (Coenen and Díaz López 2010; Markard and Truffer 2008; Geels, Hekkert, and Jacobsson 2008; Hekkert and Negro 2009). External factors here refer to aspects that are not considered to be integral factors to the formation of a specific technological innovation, but that may still influence the development and diffusion of the TIS.

This criticism of the TIS function approach highlights a research gap pertaining to the system boundary debate. Should the focal system alone delimit the system or are there are additional determinants of the system that are not part of the integral

functions? And if they are influential system determinants, should these factors be considered endogenous to the system? An attempt to address these questions is undertaken in Ch. 3, 4 and 6.

Framework Conditions – Institutions

Other system determinants, and one of the main focuses of this thesis, are framework conditions that can be described as factors that make up the environment or contextual setting in which firms innovate. Framework conditions can be supportive or interruptive of innovation activities (Gault 2010). **Institutions** have traditionally been a key framework condition to system of innovation approaches. In this thesis, the Edquist and Johnson's definition of institutions will be used. Institutions are defined as the formal and informal rules, habits, established practices, and routines underlying the relations and interactions between individuals, groups and organizations (Edquist and Johnson 1997, 46; Edquist 2005; North 1991). The type, quality and effectiveness of institutions can contribute or hinder a technological transition.

Institutions can be formal or informal. Formal institutions include laws, regulations and rights. Informal institutions includes societal codes of conduct, customs, traditions, and taboos (North 1991, 97). Institutions have been considered in the SI literature conceptually and implicitly, but a systematic and explicit consideration of different aspects of institutions, and in particular informal institutions, can still be considered a research gap. A more detailed discussion about the role of institutions in influencing socio-technical transitions will be provided in Chapter 6.

Other Framework Conditions

There are other framework conditions that can influence negatively or positively technological transitions (hindering or driving them), and that have not been formally conceptualized as part of the TIS (Hekkert and Negro 2009, 592). These framework conditions include economic and sociopolitical factors. The relevance of considering additional sociopolitical and economic framework conditions has been emphasized to a larger degree in another approach, the Multiple-Level Perspective (MLP).

Multi- Level Perspective (MLP)

The Multiple-Level Perspective (MLP), which was built on previous work by Kemp, Rip and Schot (Kemp, Rip, and Schot 2001; Rip and Kemp 1998), explains socio-technical transitions by the dynamic interaction of three different levels, namely niche, regime and landscape (Geels 2002). Niches can be described as “‘protected spaces’ such as R&D laboratories, subsidized demonstration projects, or small market niches where users have special demands and are willing to support emerging innovations” (Geels 2011, 27). The regime level “account[s] for

the stability of existing socio-technical systems”, and “include[s] scientists, users, policy makers and societal groups besides engineers and firms” (Geels and Kemp 2007, 443). The landscape level can be described as an “external structure or context for interactions of actors” (Geels 2002, 1260), which in turn can destabilize existing regimes and provide opportunities for new niche-innovations (Schot and Geels 2008).

By including the landscape level in this heuristic approach authors have more consistently raised the potential influence of factors such as economic growth, changes in oil prices, cultural values, armed conflicts, political coalitions, environmental problems and changing environmental awareness (Geels 2002, 1260; Smith, Voß, and Grin 2010, 441) in socio-technical transitions.

The MLP can be an approach that can complement the TIS approach with the identification and systematical incorporation of important framework conditions that may constrain or drive technological transitions. A more thorough literature review of the MLP framework, including its similarities, advantages, and disadvantages against the TIS approach is provided in Chapter 3.

Beyond the need of enhancing the understanding concerning which framework conditions could and should be complementing to the integral components and activities of the TIS, learning how potentially positive framework conditions, i.e., framework conditions that drive sustainable transitions, can be strengthened, or how potentially negative framework conditions, i.e. conditions that hinder sustainable transitions, can be reduced, are important endeavors.

2.4 Strengthening Positive Framework Conditions

As was mentioned in the introductory Chapter 1, environmental awareness can contribute with shifting towards a more sustainable energy mix, and this can also be considered a framework condition. Environmental psychology research has shown a correlation between environmental awareness and a higher user preference for renewable sources of energy (De Groot et al. 2012; Steg, Dreijerink, and Abrahamse 2005; Van der Werff, Steg, and Keizer 2013). Population with increased environmental awareness may impose additional pressure on government and energy providers to diversify their energy supplies towards cleaner technologies²¹. Informal lobbying can open opportunities for new technologies, such as RETs, to enter the market through organized environmental groups pressuring for environmental policies or through increasing demand from

²¹ The potential impact that public environmental awareness can have on environmental policies and regulation has been documented by Ramachandra Guha (1999) in his book ‘Environmentalism: A Global History’.

individual citizens for clean energy alternatives (Smith, Voß, and Grin 2010).²² In contrast, a lack of awareness for RETs can act as a barrier, in the form of lowered social acceptance for new technologies (Wüstenhagen, Wolsink, and Bürer 2007). In developing countries, the lack of environmental awareness and concerns for the costs and benefits of RETs have been found to have a significant negative influence on the adoption of renewable energies (Kennedy and Basu 2013; Luthra et al. 2015).

Moreover, in environmental psychology research, *problem awareness*, in this thesis denoted environmental awareness, has been found to be one of the most influential proximal determinants on behavior (Bamberg and Möser 2007). However, despite the importance of environmental awareness in explaining behavior, it should be regarded as a necessary but not sufficient condition. In other words, when positioned within two major frameworks for environmental psychology, namely *the Norm-Activation Model* (Schwartz 1977) and the *Theory of Planned Behavior* (Ajzen 1991), environmental awareness should be regarded as one out of several factors influencing behavior. For example, Bamberg and Möser (2007), who combine both frameworks, lists environmental awareness (problem awareness) together with seven other determinants of behavior, i.e., *Internal Attribution, Social Norm, Feeling of Guilt, Perceived Behavioral Control (PBC), Attitude, Moral Norm, Intention*. The result of their meta-analysis, which is based on 46 independent studies, however confirm that the total effect of awareness/knowledge of the problem “on behavior as well as intention is higher than the total effect of the more proximal determinants moral norm, attitude and PBC” (Bamberg and Möser 2007, 22). The importance of environmental awareness can be explained through its ability to influence both internal attributions, social norms and feelings of guilt, but also by directly impacting attitudes and PBC (Bamberg and Möser 2007). That said, while the inclusion of environmental awareness as part of this thesis is further motivated by the literature from environmental psychology, it should be understood as one possible factor, often indirectly influencing behaviour by affecting other factors, such as moral norm or feeling of guilt.

Given the potential influence that environmental awareness can have on behavior and consequently technological transitions, one of the Chapters of this thesis (Chapter 5) is dedicated to improving the understanding how this framework condition in particular can be strengthened. By analyzing the effect of environmental education in generating environmental awareness, this thesis will

²² See for example, P.C. Stern et al. (1999) or P.C. Stern (2000), for a detailed discussion about the Value-Belief-Norm (VBN) theory and possible avenues of influence derived from environmental awareness: i.e., Environmental Activism, Non-Activism, Private-Sphere environmentalism and Organizational actions.

also advance the knowledge of one possible strategy for strengthening environmental awareness. In addition, a deeper understanding will be gained regarding the relationship between environmental education and environmental literacy in a developing country context, namely Colombia.

Concluding Remarks

The purpose of this chapter has been to provide a review of the key background literature that has served as theoretical background of the upcoming chapters in this thesis. This chapter has also served to highlight existing limitations and research gaps. This chapter has shown the relevance of applying a systems approach for this thesis, as it gives the ability to analyze, in a structured and comprehensive manner, the complex multidimensional nature of technological transitions. The chapter has also demonstrated the advantage of the TIS function approach for identifying the potential weaknesses within technological systems. Identifying such weaknesses can facilitate the identification of appropriate policy measures to drive the expansion of technological innovations, such as RETs, which are the focus of this thesis. Furthermore, the limitations of the TIS approach have been emphasized, such as the concern of being ‘inward looking’ or predominately developed for and applied in high-income countries. It has been noted that potential lessons can be learned from other frameworks such as the MLP, which includes the socio-technical landscape, or framework conditions, in the analysis of transitions. More accurately delimiting the system to be analyzed (e.g., an RET in a particular country) based on its determinants has been raised as challenging and ongoing effort (this will be further discussed in Chapters 3, 4 and 6). Finally, improving the understanding of how potentially ‘positive’ framework conditions, e.g., environmental awareness, can be strengthened, has been stressed as another important avenue for research. Two conceptual chapters (Ch. 3 and 6) and two empirical chapters (Ch. 4 and 5) in this thesis address the questions raised and the research gaps discussed in this chapter.

Chapter 3. Technological Innovation System and the Wider Context: *A framework for developing countries*²³

3.1 Introduction

The evidence concerning the environmental, economic and human risks associated with a changing climate has brought renewable energy technologies (RETs) to the foreground in international debates as one of the most important aspects of climate change mitigation (IPCC 2012).²⁴ The necessity to move from fossil fuels to renewable sources of energy in order to curb greenhouse gas (GHG) emissions has resulted in worldwide commitments accompanied by a significant increase in resources targeting new investments in RETs.²⁵ Moreover, according to the International Energy Agency (IEA), RETs have made significant gains in cost-competitiveness and many are today considered to have reached a level that is competitive with existing fossil fuel-based alternatives (IEA 2011). RETs are also raising the importance of renewable energy policy and the need to measure and monitor renewable energy activities to support and evaluate policy implementation, especially in developing countries.²⁶

To observe the success and failures in adopting and adapting RETs analytical tools and studies are required. In an attempt to study technological innovations (see Ch. 2), in the form of RETs, in developed countries, studies have been conducted using the Technological Innovation System (TIS) function approach (Bergek and Jacobsson 2003; S. Jacobsson and Bergek 2004; Negro, Hekkert, and Smits 2007; Negro and Hekkert 2008; Negro, Suurs, and Hekkert 2008). However, the existing TIS function approach for analyzing technological innovation systems has

²³ An earlier version of this chapter has been published as a working paper at the UNU-MERIT working paper series (Eds and 2016). The paper was also been presented at the 14th Globelics International Conference (Oct. 12-14, 2016) where it received the best PhD student paper award.

²⁴ Renewable Energies, in the form of wind, solar, geothermal, small hydro, and biomass are all examples of energy derived from natural processes, which are replenished at a faster rate than they are consumed (IEA 2011). Examples of other mitigation alternatives include carbon capture and storage and carbon sinks (e.g. through reforestation) (IPCC 2007).

²⁵ In 2011, 118 countries had some form of renewable energy support policy or target for RETs at the national level, compared to 55 countries in early 2005 (REN21 2011). During 2012 fiscal year, the World Bank approved US\$3.6 billion towards financing of renewable energy projects, which represented 44% of the World Bank's total annual lending (The World Bank 2012b).

²⁶ Global projections estimate that global emissions in developing or emerging countries will exceed that of the developed world in the next decades (EIA 2013).

limitations. Firstly, the framework has been constructed from a developed country perspective and cannot be directly applied in developing countries, without first considering their characteristics. Secondly, the TIS function approach has been criticized for being *inward looking* and not sufficiently incorporating the contextual factors that may influence the success or failure of RETs diffusion.

This chapter addresses these constraints by adding to the number of functions of the TIS. This process is informed by an examination of previous attempts to utilize the TIS function approach in developing countries, and by drawing on lessons from the Multi-Level Perspective (MLP) approach. The result is an extended TIS function approach, with functions that are applicable in developing countries, and with framework conditions that reflect the socio-economic context present in many of these countries.²⁷

In this chapter, reflections and suggestions are made that can benefit future studies of technological transitions in a general sense, i.e., regardless of a specific technology. However, as indicated in the introduction, the aim of this chapter is to understand how the TIS framework can be enhanced so it can be used to understand the transition to RETs. Consequently, suggestions provided in this chapter have been developed with renewable energy technologies in mind.

3.2 Technological Innovation System (TIS)

Since the emergence in the mid-1980s of Systems of Innovation (SI) as an analytical framework and a policy tool, various IS approaches have been developed and are widely covered in the literature. The IS approaches include the National Innovation System (NIS) (Freeman 1987; Lundvall 1992; Nelson 1993), Regional Innovation System (RIS) (Cooke, Uranga, and Etzebarria 1997; Saxenian 1994), Sectoral Innovation System (SIS) (Breschi and Malerba 1997), and Technological Innovation System (TIS) (Carlsson and Stankiewicz 1991). The NIS and RIS focus on a geographical area and the SIS on an industrial sector (Hekkert et al. 2007). The TIS which focuses on a technology has been defined “as a

²⁷ No single definition of the term developing country is recognized internationally; however the term includes a multitude of countries, the developmental status of which varies widely. In this chapter (and in the rest of the thesis), the World Bank definition of developing countries, based on categories of income will be followed. Based on fiscal year 2015, countries with a Gross National Income (GNI) per capita of less than US\$ 1,045 (Low-income), US\$ 1,046-4,125 (Lower-middle-income) and US\$ 4,126-12,735 (Upper-middle-income) are considered developing (The World Bank 2015b). The suggested function changes and framework conditions proposed in this chapter have been developed with middle-income developing countries in mind.

network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology” (Carlsson and Stankiewicz 1991, 94). Despite their development as different approaches they are interrelated, i.e., a technology specific IS (TIS) could operate at the National, Regional and/or Sectoral level (Markard and Truffer 2008).

3.2.1 Setting the Boundary of TIS

Setting the boundary of a TIS is a complicated undertaking. As suggested by Carlsson and Stankiewicz (1991), the TIS could be delimited by the sector of a technology, e.g. wind or photovoltaic sector. Another suggestion is to delimit the TIS “in terms of activities” (Edquist 2005, 15). TIS literature has referred to the focal TIS as “the realm where systematic interdependencies in a specific technological field play out” (Bergek et al. 2015, 52). But what would be considered a relevant innovation activity or what systematic interdependencies would be encapsulated in the focal TIS? If a narrow boundary is set, are there relevant dependencies outside the delimited TIS that are being missed? Edquist (2005, 15) argues that understanding the various activities and their relative importance for any innovation system is “subject to change as our knowledge increases”. This chapter contributes to the above TIS framework boundary debate through the development of an extended TIS framework that explicitly considers additional factors critical for the development and adoption of a technology in a developing country context. A more elaborate discussion concerning the system boundary is provided in Chapter 6, including considerations for delimitating TIS systems in countries with different socio-economic levels.

3.2.2 Stages of Development

In order for a new technology to reach the final phases of development, diffusion and utilization, it must first undergo a *formative stage*. At this stage, various components necessary for the formation of the TIS are taking shape, e.g. knowledge accumulation, necessary infrastructure and institutional configurations (Bergek, Jacobsson, and Sandén 2008). Depending on the technology in question, market conditions as well as on actions taken by policy makers and industry actors this cumulative change of the different components of the TIS may last for decades (Van de Ven and Garud 1989).

After the development of essential structural components, the TIS enters a *growth stage* where positive feedback is established between components, contributing to an accelerated development of the system. It should be noted that negative feedback loops are also possible, which may hamper growth. However, if a momentum is created by positive feedback loops, this can make the system “increasingly self-sustained” and eventually becomes a stable and mature structure, “resilient to external pushes and pulls” (Bergek, Jacobsson, and Sandén 2008, 577–

78). This can be contrasted to the earlier formative stage where exogenous factors may assert more influence on the system (Raven 2005).

In short, the TIS framework can be used to analyze both the formation and growth of technological innovation systems (T. Jacobsson and Jacobsson 2014). A TIS analysis in developing countries would, in most cases, be focused on the formative stage, rather than on a later growth stage. Consequently, the exogenous factors could be of greater importance when mapping and analyzing TIS systems in developing countries.

3.2.3 TIS Function Approach

In 2001, Johnson and Jacobsson introduced system functions to the TIS approach in order to analyze the processes integral to the creation and development of a technical innovation system. Separately studying the underlying processes that make up the innovation system supports a systemic analysis that can help to identify characteristics of the system, such as weaknesses and strengths (Lundvall et al. 2002; Hekkert et al. 2007).

The dynamics of a technical system are considered a consequence of the interaction between different functions (Johnson and Jacobsson 2001). Thus, a comprehensive analysis of the functions of the TIS may also allow for a better understanding of the dynamics within the system. Moreover, the function approach can reveal important lessons concerning the drivers and barriers within a system, by identifying the performance of different functions. These lessons in turn can assist in devising policies for generating, diffusing and utilizing a new technology.

Over the last decade several authors have tested, adopted and further developed the TIS function approach, resulting in different versions of system functions lists.²⁸ The many sets of system functions suggest that the TIS function approach is still in a developmental stage and continued changes will be needed as the understanding of the system function advances (Edquist 2005). This chapter uses the list of system functions presented by Hekkert et al. (2007) (see Table 3.1). This list has been chosen as the preferred baseline for this chapter, as it has been used in several empirical studies and the relevance of the functions has been demonstrated.²⁹ In addition, all of the functions by Hekkert et al., (2007) fit into the OECD Oslo manual definition of innovation activities (OECD/Eurostat 2005).

²⁸ See for example: Bergek et al. (2008); Edquist (2005); Hekkert et al. (2007); Hillman et al. (2008); Jacobsson and Bergek (2006); Johnson and Jacobsson (2001); Suurs and Hekkert (2009).

²⁹ See for example: Negro et al. (2007; 2008).

Table 3.1 Innovation System Functions

System Functions		Description
F1	Entrepreneurial Activities	Activities concerning the new technology (projects started, planned etc.)
F2	Knowledge Development	Existing and new knowledge created regarding the technology (R&D, experimentation etc.)
F3	Knowledge Diffusion	How and to what extent knowledge regarding new tech. is shared among actors (number of workshops, conferences etc.)
F4	Guidance of the Search	Expectations set by government for new technology in terms of regulations and specific targets
F5	Market Formation	Market entry assistance for new tech. (protected space ('nursing') for niche market, new environmental standards, tax exemptions, feed-in tariffs etc.)
F6	Resource Mobilization	Funds allocated by government or industry towards R&D (Human Capacity) or Subsidies (Financial Capacity) for the tech.
F7	Creation of Legitimacy	Advocacy for new tech. (Lobbying to increase legitimacy and support for new tech.)

Source: Hekkert et al. (2007).

Note: The description of the functions is provided in a concise format. For a more elaborate discussion of the functions see Hekkert et al. (2007).

Most lists of functions, including Hekkert et al. (2007), have been primarily developed for, and applied in, a developed country context, where a technology has achieved a later growth stage. However, with an appropriate adjustment to the list of functions along with the inclusion of relevant exogenous factors in the analysis, the function analysis in a developing country context is relevant. It should be noted that even though the adjustments and additions to the TIS function approach proposed in this chapter have been made with a middle-income developing country in mind (see footnote 11), possible relevance of some of the proposed changes in high-income (developed) countries cannot be excluded. Mapping the functioning of the innovation system at an early formative stage will provide important information regarding the status and trends of processes considered essential for achieving the later growth stage of generating, diffusing and utilizing the technology in question. The following section will discuss some limitations raised in previous literature concerning the TIS and specifically the function approach. Next, suggestions for general improvements to the function approach, along with specific aspects relevant for its application in a developing country context will be provided.

3.3 Limitations of the TIS Approach

3.3.1 Limitation 1: Inward looking

While the TIS function approach has been credited with being a useful tool for analyzing dynamic processes, the approach has been criticized for not sufficiently taking into account the influence of external factors on the technological innovation system (Coenen and Díaz López 2010; Markard and Truffer 2008; Geels, Hekkert, and Jacobsson 2008).³⁰

Markard and Truffer (2008, 610) refer to the TIS approach as “myopic with regards to the explanation of technological transitions”. They elaborate by describing the system perspective as being “inward oriented and does not pay much attention to the system’s environment” (Markard and Truffer 2008, 610). The recognition of the potential influence of the external landscape is not a new notion but was already emphasized by Gunnar Myrdal in 1957, when he argued that a principal scientific task is “to analyze the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes” (Myrdal 1957, 18). In other words, what the authors emphasize is that beyond the boundary of the focal technological innovation system, there is an external context that may influence the system in a positive or negative manner. Over the years, the “structures and processes inside a focal TIS are generally well conceptualized in the literature” (Bergek et al. 2015, 53). However, given that a technological sector would need to be geographically delimited, i.e., nationally or perhaps even internationally, accurately defining a boundary for a TIS is not an easy task (Edquist 2005). A focus on the focal TIS has meant that “what happens outside and across the system boundary has been less systematically worked out” (Bergek et al. 2015, 53).

To clarify, the criticism of the myopic nature of the TIS approach is partly justified but not entirely. Some of the early TIS literature does mention the relevance of a wider context, referring to the potential influence of other external systems and national system-level factors.³¹ However in a recent paper by T. Jacobsson and S. Jacobsson (2014, 820), they acknowledge a lack of explicit reference to this wider context in subsequent analyses, which can partly be explained by “taking for granted certain features in the disciplines from which TIS emerged”.

³⁰ In this context external factors refer to aspects that are not considered to be integral internal factors to the formation of a specific technical innovation process (e.g. organizations and individuals directly contributing with specific knowledge, technical skills and resources), but that may equally assert influence on the TIS.

³¹ See for example: Ehrnberg and Jacobsson (1997); Jacobsson and Johnson (2000); and Johnson and Jacobsson (2001).

More importantly, the wider context has not sufficiently been systematically integrated to complement the existing focal TIS function analysis.³² Given that one of the purposes for adding functions to the TIS analysis was to be able to produce concrete policy suggestions for enabling development and diffusion of new technologies, the lack of systematically incorporating the wider context into the analysis constitutes a limitation to the approach.

Consequently, by neglecting the wider context in the analysis, the comprehensiveness of the TIS function approach may be reduced, which could result in incomplete policy recommendations that leave out essential aspects concerning existing drivers and barriers for the system. Given that exogenous factors may potentially have a stronger influence at the formative stage (Raven 2005), the lack of explicit recognition and analysis of the wider context can be of greater concern when applying the TIS function approach in a developing country.

3.3.2 Limitation 2: TIS Function Approach is Based Primarily on Developed Countries

The TIS function approach has been developed for, and primarily applied in, developed industrialized nations such as the Netherlands, Sweden and Germany (see e.g., S. Jacobsson and Bergek 2004; Negro, Hekkert, and Smits 2007; Negro, Suurs, and Hekkert 2008; Negro and Hekkert 2008; Suurs and Hekkert 2009), but its application in developing countries has been limited.

In fact, several authors have even questioned the applicability of the innovation system approach to developing countries (see e.g., Arocena and Sutz 2000; Schott and Wickstrom Jensen 2008; van Alphen, Hekkert, and van Sark 2008). Schott and Wickstrom Jensen (2008) argue that without considering the specific context, the innovation system approach cannot be applied to developing countries. The context may involve institutions, the socio-economic environment of the country, and existing dynamics within the country (Arocena and Sutz 2000).

Other studies, on the other hand, while recognizing that the TIS framework was developed mostly for developed countries, they have tested it in emerging economies such as China and India. In Gosens and Lu (2013)'s study of wind power development in China, the authors highlight the importance of not only considering the domestic technological system but also looking at the relation between the domestic and the global technological system. The authors caution that the large domestic market in China and India might be a unique contributing factor to the development of the TIS in these countries, and thus the process may

³² An exception being the inclusion of the function “development of positive externalities”, referring to positive external economies (see e.g., Bergek, Jacobsson, and Sandén 2008).

not be applicable to smaller developing economies. Klagge et al. (2012) also raised a similar point in their analysis of the Chinese wind energy sector.

Radhika Perrot applied the TIS function approach to analyze the transition of renewable energies in South Africa and India (2012). The paper provides some interesting insights into the case of the South African and Indian technical innovation systems. The article points out that existing frameworks do not sufficiently take into account the context of developing countries and that “there is a pressing need to develop new analytical frameworks when analyzing renewable energy industries in developing countries” (Perrot 2012, 8).

3.4 Energy Transitions in Developing Countries

According to the World Bank, 135 countries are considered developing countries, 63% of the world’s countries (The World Bank 2016b). The vast variety of characteristics encapsulated in this category of countries emphasizes the complexity in designing a generic framework for developing countries. Notwithstanding, the suggestions proposed in the following section have been made while considering commonalities found in developing countries.

Global projections have estimated that GHG emissions in developing or emerging countries will exceed those of developed countries over the next decades (EIA 2013). These projections emphasize the need for developing countries to divert from the carbon intensive development path that characterized today’s developed countries. By ‘leapfrogging’ over the carbon intensive stage, developing countries can therefore avoid the ‘carbon lock-in’ experienced in many developed countries (Watson and Sauter 2011). Leapfrogging in terms of technology refers to “the implementation of a new and up-to-date technology in an application area in which at least the previous version of that technology has not been deployed” (Davison et al. 2000, 2).

Given that most technologies have been created in developed countries, a transfer of technology from developed to developing countries must occur to enable leapfrogging (Gallagher 2006). Beyond the transfer of the technology, a successful technology leapfrogging is dependent on appropriate organizational structure changes and appropriate policy reforms (Steinmueller 2001; Perkins 2003). With the list of functions provided by Hekkert et al. (2007) as a starting point, the following section will provide suggestions for how this framework can be adjusted to improve its applicability in developing countries.

3.5 Suggestions for the Function Framework

3.5.1 Suggestion 1: Function 2 - Knowledge Development and Creating Adaptive Capacity

Since most technologies were created in developed countries, several authors have stressed the need for placing attention on technology transfer and technological absorptive capacity (Cohen and Levinthal 1990; Arocena and Sutz 2001; IPCC 2001). Most of the absorptive capacity research has focused on the firm level (Criscuolo and Narula 2008). Absorptive capacity at the firm level has been described as the capability of firms to digest and utilize external knowledge (Cohen and Levinthal 1989). A recent study by Peuckert, Bodenheimer and Gandenberger (2016), specially looked at the role of international trade for domestic development of the wind energy sector in developing countries.³³ Several studies have used various forms of research and development (R&D) as a proxy to measure absorptive capacity of firms (Flatten et al. 2011).³⁴ In the TIS function list chosen for this chapter (Hekkert et al. 2007), however, R&D is referred to as a proxy for knowledge development for a particular technology (see Table 3.1: function 2).³⁵ In this chapter, R&D will be associated with the development of new technological knowledge domestically, rather than the absorptive capacity of external knowledge.³⁶

This does not imply that absorptive capacity should be ignored in the TIS function approach. On the contrary, the ability of countries to assimilate and utilize external knowledge is highly relevant, especially in a developing country context, where transfer of technology is common practice. The focus however, when discussing the transfer of technology, should be on the capability of countries to successfully receive the technology in question. Therefore, a better proxy than R&D for assessing the absorptive capacity of countries at the receiving end of a technological transfer is their level of technical and higher education (Mowery and Oxley 1995). Beyond formal technical and higher education, learning by Doing,

³³ Their study identified e.g., an increase in domestic patent applications after imports occurred for the specific sector.

³⁴ See Oltra and Flor (2003) for an example of R&D input (intensity), and Ahuja and Katila (2001) for an example of R&D output (patents). See Flatten et al. (2011) for a more extensive list of studies using R&D as a proxy.

³⁵ Hekkert et al. (2007) refer to this function as including learning by searching and learning by doing.

³⁶ The use of R&D (input and output) to measure the knowledge creation/development function of the TIS is widely used. See Bergek et al. (2008) for an extensive comparative list of TIS functions.

Using and Interacting (DUI), is another potential mode of learning (Lundvall 1992).

In addition, in the developing country context, attention should also be directed towards the institutional and organizational capacity to receive a new technology. This necessitates a wider focus on the national absorptive capacity, rather than the sole attention of the absorptive capacity of firms. A country's national absorptive capacity can be defined as "the ability to learn and implement the technologies and associated practices of already developed countries" (Dahlman and Nelson 1995, 88).

An example where this has been tested is in the study by van Alphen, Hekkert and van Sark (2008, 166), which analyzed the diffusion of RETs in the Maldives. They refer to "the development and strengthening of human, organizational, and institutional capacity" as *creating adaptive capacity*. They chose to replace the *knowledge development* function with *creating adaptive capacity*, which was motivated by arguing that the Maldives is not "capable of developing the appropriate technology domestically" (van Alphen, Hekkert, and van Sark 2008, 166).³⁷

While replacing the knowledge creation function with an adaptive capacity function may have been motivated in the case of the Maldives, there are reasons for caution when discussing a general framework for developing countries. When considering a framework to be used in developing countries, replacing *knowledge development* with *creating adaptive capacity* may lead to missing important information concerning knowledge development trends or learning curves. In other words, even though the country under study may not be capable of domestically developing the technology, there may still be on-going knowledge development in the form of research projects or experimentation for a specific technology.

In that respect, it is important to recognize the wide discrepancies between developing countries in terms of their ability to develop new knowledge. For example, expenditure on R&D differs widely among developing countries (low, lower-middle, upper-middle income). In 2012, El Salvador spent 0.03% of GDP on R&D, compared to 1.92 % of GDP spent by China (The World Bank 2015a).³⁸ The varying levels of R&D expenditure would suggest different capabilities for domestic knowledge development amongst developing countries. Moreover, the capability for knowledge development of a developing country is not static but

³⁷ Van Alphen et al. (2008) began with Hekkert et al. (2007) as a baseline (function) list.

³⁸ The data include both private and public R&D expenditure for basic research, applied research, and experimental development.

changes over time, along with its ability to shift from purchasing technologies to adapting or developing technologies domestically.

India and China represent two examples that demonstrate developing countries' ambition to rapidly move from buying technology from industrialized countries to manufacturing and developing it. Within a span of about 10 years, China and India went from importing all wind turbines from foreign companies to having a large domestic manufacturing industry and prominent RET companies (Lewis 2007). Put differently, India and China transitioned from an early formative stage to a growth stage with widespread generation, diffusion and utilization of a new technology within a decade. Incrementally improving their knowledge creation played an essential part in moving China and India from the formative to the growth stage. Earlier literature has also emphasized the importance of recognizing the potential of developing countries of improving technologies or adapting them to the local context (Fransman 1982; Voss 1988).

The examples of the China and India represent an extraordinary rapid transition from an early formative stage to growth stage. This transition may take much longer, or perhaps never fully occur, in other developing countries. However, given the dynamic quality of knowledge development in developing countries, the inclusion of the knowledge development function in future TIS studies should be considered. Moreover, recognizing the influence of knowledge development in cases that have successfully moved from purchasing technology to domestic innovation further motivates this approach.

To conclude, the first suggestion of this chapter is that new *knowledge development* in a TIS function analysis could be mapped by reviewing R&D (input and output), but should be analyzed separately from *creating adaptive capacity*. The former will strictly assess new knowledge being created, which can be analyzed by mapping the number of research projects, R&D expenditure, and patents relating to the technology in question. Considering including *knowledge development* in a developing country study may alleviate the risk of missing valuable information concerning knowledge trends. The latter (i.e., *adaptive capacity*) will evaluate the readiness of a particular country to receive a new technology, which can be done by mapping the existing level of human, institutional and organizational capacity. A proxy for human capacity can be the level of technical and higher education in a country.

3.5.2 Suggestion 2: Function 6 – Resource Mobilization

The second suggestion to better adapt the function approach to a developing country context is to split the resource mobilization function (F6) (see Table 3.1) into two categories of resources. Most developing countries receive grants and loans for technical assistance (e.g. for human capacity building) and financing of projects for renewable energies and other mitigation efforts from bilateral and

multilateral organizations. International financing also involves Foreign Direct Investment (FDI) and other sources such as carbon offsets or specific climate change funds or through the Clean Development Mechanism (CDM).

International investments in clean energy in South America, Middle East and Africa, and Asia and Oceania, grew by more than 400% between 2005-2009 (Limaye and Zhu 2012). Therefore international resource mobilization towards renewable energies and other mitigation efforts play an important role for developing countries and regions. For example, in May 2014, the Global Environment Facility (GEF) had 25 projects (out of 53 executed by the Inter-American Development Bank) dedicated to energy efficiency, renewable energy and carbon markets, totaling US\$301 million (IDB 2015a). Previous research has emphasized the potential for CDM to go beyond the financial aspect to also contribute to technology transfer (Popp 2011; Murphy et al. 2015). The issue is however divided, with other studies demonstrating a less pronounced effect on technology transfers from CDM (Das 2011; Spalding-Fecher et al. 2012).

Including an analysis of international resource mobilization towards RET in developing countries would most likely provide a more accurate assessment of function 6. The suggestion is therefore to split function 6 into two categories, (F6a: *resource mobilization (government)*) and (F6b: *resource mobilization (international loans and grants)*), in order to analyze domestic resources and international resources separately. The international resource function could be analyzed by examining the availability, size and type (human and/or financial) of international resource mobilization for the technology in question.

3.5.3 Suggestion 3: Function 7 - Creation of Legitimacy/Advocacy Coalition

Enhanced legitimacy for a new technology can potentially influence several other functions, such as increased resource mobilization (F6) or improved tax regimes (F5) (Hekkert et al. 2007). Hekkert et al. (2007) have mapped the advocacy coalition/creation of legitimacy function through changes in interest groups and their lobbying activities, as well as public support and acceptance. The lobbying groups in these studies are generally organized, well financed and often with political and economic interests and influence, such as firms, government, knowledge institutions, NGOs or environmental groups. Industries can for example utilize their existing financial strength to form specialized divisions responsible for lobbying upon their behalf (Unruh 2000).

However, lobbying can also occur from groups of people that lack initial organization, financial strength or economic and political influence. This form of lobbying may involve engaged individuals and smaller environmental or university research groups, advocating for clean technologies. Negative lobbying, i.e., resistance to new technologies may also be present in the form lack of social

acceptance, e.g. resistance to the visual impact of wind energy (Wüstenhagen, Wolsink, and Bürer 2007).

The emergence of the Internet, and subsequently the information age, has revolutionized the way information is shared and accessed. Social media in the form of blogs, twitter, Facebook and YouTube allow for public opinion to be shaped at a speed that was not possible a few decades ago. In recent years, the forming of public opinion on social media has been accredited as an important force for political change, such as the Presidential election of Barack Obama, the 2011 demonstrations in Spain and the ‘Arab Spring’ (Qualman 2009). Internet access in developing countries has steadily risen in the last decade (see Fig. 3.1), which facilitates expression of public opinion. Clearly a wide discrepancy exists in Internet users across developing countries, e.g. 1/100 people in Burundi to 68/100 people in Malaysia, and the usefulness of this suggestion will need to be decided based on the country under study (The World Bank 2016e).

Figure 3.1 Internet Users in Developing and High Income Countries (per 100 people)

Source: The World Bank, 2016.

However, for the purpose of a general framework, the rise of Internet users in developing countries enable, particularly in upper-middle income countries, for a new form of lobbying (e.g., through social media), which may influence other TIS functions e.g., guidance of the search or resource mobilization. The argument is therefore made that it would be beneficial to separately analyze this relatively new form of lobbying when mapping activities for function 7 (legitimacy and advocacy coalition). The suggestion is therefore to split function 7 into two categories, namely *formal* (F7a) and *informal lobbying* (F7b). Formal lobbying refers to

legitimacy and advocacy coalition exercised by well-established lobbying groups with economic and political weight, while informal lobbying includes advocacy by smaller groups (e.g., environmental groups), associations or individuals. One way to examine informal lobbying can be through changes in public opinion, support and acceptance expressed in social media for the technology in question. This split also holds relevance for future TIS function analyses in high-income countries. A limitation of Suggestion 3 is in developing countries where access to Internet is very low, e.g., low-income countries; the suggested split of function 7 may lose its relevance.

3.5.4 Suggestion 4: Incorporating the External Landscape

The fourth and last suggestion relates to the concern that the TIS approach does not sufficiently account for factors beyond the activities of the actors in the focal technological innovation system, i.e., concern of being too *inward looking*. While it is possible to find a theoretical discussion in the TIS literature concerning the relevance of the wider context, the TIS function approach has not sufficiently included explicit contextual factors as part of the framework that would enable a systematic empirical analysis of the wider context. Therefore, the following section will discuss how the TIS function approach could incorporate lessons from the Multiple-Level Perspective (MLP) about the wider context, as a systematic manner to complement the existing TIS function approach. This section will begin with a general discussion about the TIS and MLP by reviewing the existing literature. This will be followed by a set of explicit contextual factors based on MLP literature along with conditions found in many developing countries that may have an influence on the Focal TIS.

Learning from MLP

While the MLP and the TIS are both rooted in evolutionary economics and share the same conceptual basis such as path dependency, lock-in and nonlinearity, the two analytical frameworks have formed separately from one another over the last two decades. While the TIS is concerned with *institutions*, *actors* and *networks* to help explain the performance, growth and decline of a technology, the MLP refers to niche, regime and landscape *levels* when analyzing technological transitions (see Table 3.2). More specifically, the principal postulate of the MLP is that transitions occur from an interaction between the three levels, where landscape levels creates pressure on the regime, which in turn can destabilize existing regimes and provide opportunities for new niche-innovations (Schot and Geels 2008).

Table 3.2 Integral TIS and MLP Elements

Technological Innovation System (TIS)	Multi-Level Perspective (MLP)
<p>Actors Organizations and individuals that contribute to the development of the technology (Hellsmark and Jacobsson 2009).</p> <p>E.g. Associations, research institutes, firms, financial institutions, governmental agencies or policy makers each with specific competences, resources and strategies (Carlsson and Stankiewicz 1991).</p>	<p>Niche Level (Micro) “Niches are ‘protected spaces’ such as R&D laboratories, subsidized demonstration projects, or small market niches where users have special demands and are willing to support emerging innovations” (Geels 2011, 27).</p>
<p>Networks Interlined network of different actors; Interactive learning (e.g. university-industry networks or user-supplier) and formation of political networks (S. Jacobsson and Lauber 2006; Bergek, Jacobsson, and Sandén 2008).</p>	<p>Socio-Technical Regime (Meso) “Account for the stability of existing socio-technical systems”, and “include scientists, users, policy makers and societal groups besides engineers and firms” (Geels and Kemp 2007, 443).</p>
<p>Institutions “Sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups” (Edquist and Johnson 1997, 46).</p>	<p>Socio-Technical Landscape (Macro) An external environment consisting of factors that influence both the regime and the niche level. “Set of heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems” (Geels 2002, 1260). Growing environmental awareness (Smith, Voß, and Grin 2010).</p>

Source: Author tabulation.

Complementary Characteristics

Despite their disconnected development path, several authors have recognized the various overlapping and complementary characteristics between the TIS and MLP (Coenen and Lopez 2010; Weber and Rohracher 2012). For example, Coenen and Lopez (2010) highlighted that the concepts from one framework include aspects that are considered a weakness in the other framework. For example, while one of the strengths of the TIS is its capacity to analyze dynamic processes (Hekkert et al.

2007), the analysis of the interaction between actors, institutions and networks is considered a weakness of the MLP (Farla et al. 2012; Smith, Stirling, and Berkhout 2005). In contrast, the lack of analysis of the socio-technical regime and socio-technical landscape in the TIS framework is considered one of the strengths of the MLP (Markard and Truffer 2008; Weber and Rohracher 2012). Geels et al. (2008, 530) make a similar point by stating that, even though both TIS and MLP utilize levels in their analysis, “it seems fair to say that the MLP has progressed further in conceptualizing interactions between internal and external processes”.

The complementing aspects of the two frameworks have resulted in two recent attempts to combine the MLP and TIS (Markard and Truffer 2008; Meelen and Farla 2013). The paper by Markard and Truffer (2008) explains the interaction between the elements of the multi-level framework and the TIS, where it is apparent that the TIS primarily concerns the niche level, while partly analyzing existing regimes but leaving out the potential effects generated by the landscape level (Fig. 3.2). As was briefly discussed in section 3.3.1, fully leaving out the landscape level or wider context is not an accurate description of the TIS approach, but rather a lack of explicitly and systematically analyzing socio-economic landscape factors. While the purpose of this chapter is not to integrate the two frameworks, but rather to propose complementary additions that could benefit the empirical application of the existing TIS framework, the model by Markard and Truffer (2008) emphasizes an important point, namely that the TIS approach can learn from the MLP to explicitly analyze the influence of the landscape level.

As stated before, while the landscape factors have been emphasized to be influencing both existing regimes and the TIS, these factors have been mostly left out of empirical analyses. Two studies that have attempted to incorporate the wider context as shown in Figure 3.2, are Markard, Stadelmann and Truffer (2009) and Wirth and Markard (2011). The former, which empirically analyzed biogas development in Switzerland, emphasized the role of landscape factors, such as changes in environmental laws and climate change; but they do not engage in a deeper analysis concerning the influence of other landscape factors. The latter empirical study solely focuses on the impact of other competitive or supporting TIS, along with a deeper analysis of existing socio-technical regimes. Bergek et al. (2015) highlight the need for conceptualizing the interaction between the focal TIS and its context, while also suggesting four context structures.³⁹ Moreover, they emphasize the existing research gap, and one of the main contributions of this chapter, namely the need for understanding contextual structures in developing or emerging countries.

³⁹ The four context structures suggested are: industrial sectors, geographical territories, other TISs and political structures.

Figure 3.2 Interaction between TIS and MLP

Source: Adapted from Markard and Truffer (2008, 612)

This study has chosen to use the terminology ‘landscape factors’, rather than context structures, given that the suggested landscape factors in this chapter will be to a large extent based on a review of the MLP literature.⁴⁰ Using the MLP literature to assist in selecting relevant landscape factors is justified by the more extensive conceptualization made by MLP approach of the wider context (Markard and Truffer 2008).

The next section will discuss landscape factors relevant for developing countries, and which could be systematically integrated as a part of the existing TIS function approach. This will contribute to addressing an existing gap in the literature, while also improving the comprehensiveness of future empirical TIS studies. As

⁴⁰ It should be noted that the socio-technical landscape factors is the complete denotation used in the MLP approach. For simplicity, the term landscape factors will be used throughout this chapter.

previously mentioned, in this chapter, a specific focus is placed on the transition of technologies that could advance sustainable development. Consequently, RETs are central in the discussion and selection of the following landscape factors.

Landscape Factors Influence on TIS in Developing Countries

Changes in external landscape factors can contribute to positive change (towards sustainable transition) by providing pressure on existing regimes and create possibilities for niche development (Schot and Geels 2008). Smith et al. (2010) argue that while landscape factors can generate opportunities for niche developments they can also negatively influence transition to more sustainable technologies by reinforcing the existing trajectory of a regime. The notion that factors exogenous to the focal TIS influence the “strengths of the functions” is widely accepted and emphasized in the TIS and MLP literature (Bergek, Jacobsson, and Sandén 2008, 579). As depicted in Table 3.2, the landscape or socio-technical landscape has been defined by Geels (2002, 1260) as a “set of heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems“. Growing awareness concerning environmental sustainability and the role of renewable energy has also been identified as a landscape process, which by questioning existing regimes can create opportunities for niche development (Smith, Voß, and Grin 2010).

Given the vast complexity and multitude of factors existing in the landscape level it will not be possible to incorporate all aspects. Based on the factors of the socio-technical landscape raised by Geels (2002), Smith et al. (2010), and others, along with the justifications provided below, six Landscape Factors (LF) are selected to complement the existing TIS function approach in a developing country context. The proposed landscape factors are: *Economic Growth, Environmental Awareness, Climate Change, Armed Conflicts, Corruption and Inequality (Unequal Access to Higher Education)*. The proposed list of landscape factors consists of nationally bound factors along with those transcending the national level.

Certain landscape factors will also be relevant in developed countries. However, as previously mentioned, including a more comprehensive landscape factor analysis is particularly relevant when performing a TIS analysis in developing countries. This position is based primarily on two specific aspects found in many developing countries. The first aspect relates to the reasoning made by Rob Raven (2005, 2010), that system components (functions) are not fully developed in the early formative stage of a system, which results in a larger influence from exogenous factors. Since TIS in many developing countries can be described to be in an early formative stage, an emphasis on exogenous factors (landscape factors) is justified. This does not suggest to imply that exogenous factors will necessarily discontinue their influence on the TIS after a technology has left the formative stage and entered the growth stage. The second aspect is that some of the landscape factors

that are being proposed are generally stronger and more dominant in many developing countries, e.g., corruption, unequal access to education and armed conflicts. This higher prevalence of landscape factors and how they may influence the TIS functions in developing countries will be discussed in greater length below.

Landscape Factor 1: Economic Growth

A tight coupling between increased economic activities and energy demand has been demonstrated (D. I. Stern 2004). With four countries (Saudi Arabia, Iran, Iraq and Kuwait) responsible for about half for the World's oil reserves, price volatility for oil has contributed to increased long-term energy insecurity (Sadorsky 2009). In the interest of tackling energy insecurity and sustaining economic growth, energy production from renewable energy sources offers an alternative to these concerns (Dincer 2000; Sadorsky 2009). Given that the majority of the increase in energy demand in the future will come from developing or emerging countries, it is relevant to better understand the influence of economic growth on a developing country focal TIS system.⁴¹

Economic growth is also correlated with an increased availability of government resources as a result of higher tax revenues. Increased availability of government resources does not necessarily result in more subsidies, tax reductions, or R&D investments beneficial for RETs, as this also depends on aspects such as political will, government policies, strength of advocacy groups, etc. However, it is fair to assume that the likelihood for more resources being mobilized towards RETs will be improved with additional public and private resources available.

While increased economic growth contributes to government revenues, a decline in economic growth due to domestic and/or international events may also prove conducive to technological change. Economic growth may in fact generate inaction from dominant actors with the preference of preserving the existing regime, while an economic decline or recession may create pressure on government and existing regimes for change (Geels 2013). The 2008 financial crisis, for example, arguably provided a 'window of opportunity' for transitioning towards more sustainable energy sources during the early years of the crisis (Geels 2013, 93). In other words, a financial crisis may enhance the demand for change from the incumbent system, which could contribute to legitimizing (function 7) new technologies such as RETs. The opposite may also occur, where a financial crisis may redirect attention away from sustainability issues towards shorter-term concerns such as employment opportunities and securing personal income.

⁴¹ China and India alone are expected to drive 45% of the World's increased energy demand between 2005-2030 (IEA 2007).

Whatever the impact of economic growth, i.e., positive or negative, its potential influence as a landscape factor on technological transition justifies its inclusion in the landscape analysis. The changes in economic growth can be mapped by tracking changes in the Gross Domestic Product (GDP) and domestic and international economic events, along with their influence on TIS functions such as resource mobilization (F6) and legitimacy creation (F7).

Landscape Factor 2: Environmental Awareness

“Growing environmental awareness is a socio-cultural development that can be considered a landscape process, and which is questioning the performance of multiple regimes, whilst generating opportunities for niches” (Smith, Voß, and Grin 2010, 441). The United Nations Environmental Programme (UNEP) describes environmental awareness as:

the ability to emotionally understand the surrounding world, including the laws of the natural environment, sensitivity to all the changes occurring in the environment, understanding of cause-and-effect relationships between the quality of the environment and human behaviour, an understanding of how the environment works as a system, and a sense of responsibility for the common heritage of the Earth, such as natural resources - with the aim of preserving them for future generations (UNEP 2016, chap. 4.2).

In this chapter, the inclusion of environmental awareness as a landscape factor for transition of RETs considers this definition of environmental awareness to be a state of mind, which facilitates an understanding of the mitigating role that RETs play, e.g. on climate change and air pollution. The inclusion of environmental awareness as a landscape factor is motivated through the assumption that an increase environmental awareness amongst actors such as civil society and government may lead to increased pressure on existing energy producing regimes to diversify towards cleaner technologies. Even though environmental awareness can be seen as a ‘softer’ ‘behind the stage’ factor, when compared to concrete policies or financial incentives directed at RETs development and diffusion, convincing arguments exist for not omitting the potential influence of environmental awareness in the context of socio-technical transitions, as will be shown in the text below. Environmental awareness is discussed further in Chapter 5.

An increase in environmental awareness in civil society may give rise to influence on both government and actors in the energy sector to invest more in clean technologies. For example, Guha (1999) has documented the potential impact that public environmental awareness can have on environmental policies and regulations. The influence can be consumer-driven (i.e., demand for energy produced from RETs) and/or through pressure, support or acceptance of

environmental policies exercised by organized environmental groups or individual citizens (informal lobbying).⁴²

Evidence from environmental psychology research has shown a link between environmental awareness and a higher preference for utilizing energy produced from renewable energy technologies (see e.g., De Groot et al. 2012; Steg, Dreijerink, and Abrahamse 2005; Van der Werff, Steg, and Keizer 2013). While, the just mentioned empirical studies were performed with data from Hungary and the Netherlands, there are several reasons for including the environmental awareness influences in developing country contexts as well. Firstly, large cross-national studies have shown that concern for the environment is equally important for developed and developing countries, including minor differences in the willingness to pay to protect the environment (Riley E. Dunlap and Mertig 1995).⁴³ Secondly, the theory of post-materialist values (Inglehart 1977; Inglehart 1990; Inglehart 1997), which has as a central argument that people of affluence and education are who primarily exercise environmental concern, does no longer exclusively apply to high-income industrialized countries. As shown in Figure 3.3, the GDP per capita income level has significantly risen in many developing countries. As a comparison, GDP per capita in upper-middle income countries, based on purchasing power parity (PPP), is almost at the same level as it was for high-income countries in the early 1990s (The World Bank 2016d).

In a similar fashion, primary and secondary enrollment rates in developing countries have increased across developing countries, with primary enrollment above 80% in all income categories (Fig. 3.4). This is not to say that the arguments made by Inglehart about post-materialist values are irrelevant, but rather to stress that affluence and education levels in many developing countries have improved significantly over the last decades.

Following the logic of post-materialist value theory, the rise in GDP per capita and education levels in developing countries suggests that the relevance for including environmental awareness in a developing country study is steadily rising. Moreover, the falling prices of RETs, such as wind and solar power, further enhance their competitiveness against conventional energy alternatives (IRENA 2015). In the context of assessing the potential influence of environmental

⁴² See for example, P.C. Stern et al. (1999) or P.C. Stern (2000), for a detailed discussion about the Value-Belief-Norm (VBN) theory and possible avenues of influence derived from environmental awareness: i.e., Environmental Activism, Non-Activism, Private-Sphere environmentalism and Organizational actions.

⁴³ The data used in Dunlap and Mertig (1995) are based on the Health of the Planet Survey (1993), which included 22 developing and developed countries.

awareness on the focal TIS, it helps to reduce a barrier, namely costs, from the equation.

Figure 3.3 Change in GDP per capita (PPP) in developing countries (1990-2014)

Source: The World Bank, 2016.

Finally, while an increasing environmental awareness can have a positive influence on emerging RETs, the absence of awareness in a population can slow down the diffusion of RETs. Specifically, the lack of awareness for new energy technologies, e.g. awareness about the benefits and costs of RETs, has been stressed as a significant barrier in developing countries (Reddy and Painuly 2004; Kennedy and Basu 2013; Luthra et al. 2015). For example, in an Indian study of barriers to RET adoption, “lack of consumer awareness to technology” together with “lack of sufficient market base” were found to be the most important market barriers, in front of aspects such as “lack of paying capacity” (Luthra et al. 2015, 770).

Awareness of the benefits and actual costs of RETs is an essential first step for both informal lobbying (F7b) carried out by individual citizens or organized environmental groups, and for consumer-driven demand to occur. Therefore, tracking changes in environmental awareness can reveal barriers or drivers at the landscape level and can contribute to making the TIS function approach more comprehensive. Environmental awareness can be analyzed by mapping changes in societal trends, which can include frequency in online discussion forums regarding sustainability and the role of RETs, changes in participation in environmental programs (higher education), changes in overall environmental awareness among

actors from existing national surveys, as well as the perceived influence of environmental awareness on system functions.

Figure 3.4 Change in Primary and Secondary Enrollment Rates in Developing Countries

Source: The World Bank, 2016.

Landscape Factor 3: Climate Change

Climate change is impacting nations in different ways, from the intensification of precipitation events leading to flooding in some parts of the world, to increased heat waves and droughts in other parts, for example (IPCC 2012). The impacts of climate variability and change may influence technological transitions in several ways, affecting other landscape factors as well as TIS functions. Climate change may influence a technological transition by creating a need for mitigation (reduction of GHG emissions) and/or adaptation (reduction of the vulnerability of the system to the impacts of climate change) efforts.

First, the economic costs of environmental disasters caused by an intensification of extreme weather events are placing a strain on businesses (LF1: Economic growth) and government resources (F6a: Resource Mobilization), in both developing and developed countries. According to the Stern review of 2006, extreme weather could, by the middle of this century, amount to losses of 0.5-1.0% of global GDP per year. The 2003 heat wave in Europe alone contributed to approximately 35,000 deaths and a loss of approximately US\$ 15 billion from reduced agricultural yields (N. H. Stern 2007). Conversely, bilateral and multilateral aid grants and loans for climate change mitigation and adaptation will positively influence available government resources (Resource Mobilization: F6b).

Second, the human and economic costs of climate change can induce awareness (LF2), which can contribute to mobilizing support and creating legitimacy (F7) for a need to modify and diversify the energy matrix. Increased awareness about climate change, however, can take different forms and lead to different transitions. In some areas, the impacts of climate variability and change on the hydrological cycle, for example, may highlight the vulnerability of current energy systems, particularly those energy systems highly dependent on hydropower. As it will be shown in Chapter 4, in the case of Colombia, a country whose energy matrix is composed mostly of hydropower, droughts induced by El Niño phenomenon have put a strain on the hydropower generation opening the space for discussions on the need to diversify the energy matrix. The diversification, however, will not necessarily be towards cleaner sources of energy, but could instead increase fossil fuel-based energy production through thermoelectric power plants. The increased awareness can also be about the risks of inaction and thus a space may be opened towards finding alternative cleaner sources of energy, such as RETs.

Thirdly, the increased attention towards the severity of a changing climate has resulted in several international agreements and commitments to curb GHG emissions, partly by increasing the share of RETs in the energy mix.⁴³ These international agreements, such as the Paris Climate Agreement in 2015, may influence the targets set by governments (F4: Guidance of the Search) and if covered in mainstream media raise public awareness (LF2) concerning the importance of climate change mitigation and adaptation. This third point is particularly important to reduce the risk of taking measures that may increase the resilience of the system to climate variability and change, but that may diversify the energy system towards dirtier sources of energy, instead of RETs. Even in countries with limited GHG emissions, and where their mitigation efforts may not significantly influence global emissions, international agreements, including the mobilization of international funds, may serve as incentives to invest in mitigation efforts, such as investing in RETs.

In short, climate change as a landscape factor has the potential to support RETs diffusion in various ways. Mostly, the impacts of climate change can weaken the existing regime, opening the space for niche growth. As mentioned above, attention needs to be given, and the appropriate policies need to be put in place, to ensure that the impacts of climate change do not lead to short-term decisions of moving towards dirtier but climate resilient sources of energy (e.g., coal and oil-based electricity production). International climate agreements and international funding options, such as the Green Climate Fund and the Clean Development Mechanism (CDM), can encourage countries to invest in alternative sources of energy that contribute both to mitigation and adaptation. This landscape factor can be analyzed by mapping climate change related events and corresponding costs along with international and domestic commitments to alter the energy mix towards sustainable sources of energy.

Landscape Factor 4: Armed Conflicts

Any form of violent conflict, whether state-based or non-state based is defined as conflict when at least 25 battle-related deaths have occurred in one conflict. Under that condition, a state-based armed conflict can be further defined as a “contested incompatibility that concerns government and/or territory where the use of armed force between two parties, of which at least one is the government of a state” (UCDP 2014).⁴⁴ A more detailed discussion regarding the different forms of conflicts and the varying impacts they pose on populations is beyond the scope of this chapter.⁴⁵ In this chapter, armed or violent conflicts will be used when discussing their possible influence on the success or failure of technological transitions.

In 2013, about 1.5 billion people across the world were impacted by violent conflicts (The World Bank 2013). A total of 38 armed conflicts, with the majority taking place in Africa (13), followed by Asia (12), Middle East (7), Europe (5) and Latin America (1) were reported during 2012 (Armengol et al. 2013). Larger macro-economic effects from armed conflicts have been widely studied and generally demonstrate a reduced income per capita, increased military expenditure, technological degeneration, damaged infrastructure as well as reduced human capital, innovation and economic growth (Abadie and Gardeazabal 2003; Collier and Duponchel 2013; Brück, Naudé, and Verwimp 2013). For example, one study (Collier 1999) estimated an annual reduction of 2.2% GDP in countries affected by conflict.

The direct impact that armed conflicts have on entrepreneurial activities has been less studied, and has so far yielded contradictory results. Ongoing conflicts have been found to provide a worsened business environment in the form of higher uncertainty and transaction, reduced markets and lucrative investment prospects, which can contribute to reduced entrepreneurial activities (Naudé 2007). However, a study by the International Labour Organization (ILO) and the Global Entrepreneurship Monitor (GEM) found an increase in new firms start-ups during the crises (Brück, Naudé, and Verwimp 2013). Moreover, there are examples throughout history for how technological innovations have occurred during armed conflicts, e.g. the development of the Internet or the invention of firearms (Humphreys 2003). Whether an armed conflict will obstruct or provide opportunities for entrepreneurial activities within renewable energy sectors, e.g. in the form of directed military R&D spending towards RETs would have to be

⁴⁴ Non-state based conflict is defined as “the use of armed force between two organized armed groups, neither of which is the government of a state” (UCDP 2014).

⁴⁵ For more details on types, cases and trends of armed conflicts, see for example: Scherrer, 2003.

scrutinized on a case by case basis. The possible influence (positive or negative) of armed conflicts on entrepreneurial activities, human capital, economic growth and technological innovation, however, justifies its inclusion as a landscape factor to complement the TIS function analysis.

By including armed conflicts in conjunction with the TIS function analysis, the aim is to better understand their influence on technological transitions by shedding light on the following type of questions: Does the cost of the conflict influence the government expenditure to the extent of hampering resource mobilization towards RETs (F6a: Resource mobilization)? Does the conflict contribute to levels of insecurity that have obstructed potential new developments of renewable energy infrastructure (F1: Entrepreneurial activity)? Does the conflict contribute to an increase in technological innovation and development? This landscape factor can be analyzed by mapping the cost of the armed conflict (as percentage of government expenditure), mentioned number of entrepreneurial activities canceled or never initiated, or new technological innovations initiated, as a consequence of the conflict.

Landscape Factor 5: National Corruption

Transparency International (2015) defines corruption “as the abuse of entrusted power for private gain”, and can involve various forms such as embezzlement, state capture, bribery, rent seeking, and nepotism. Corruption exists to some extent in all nations around the world, however, it is often more prevalent in developing countries. The presence of corruption has been argued to negatively affect democratic systems and rule of law, social trust among citizens, public resources, economic growth, and inequality (Transparency International 2014).

For the purpose of analyzing corruption as a landscape factor for the TIS, this chapter proposes to concentrate on the influence that corruption may have on entrepreneurial activities (F1), resource mobilization (F6), economic growth (LF1), and unequal access to quality education (LF6). Globally, it has been estimated that 5% of the world’s GDP is lost to corruption each year, with bribes comprising approximately US\$ 1 trillion. According to the African Union, in 2002 about US\$ 148 billion constituting approximately 25% of GDP of African States was lost to corruption (OECD 2014). The loss of public revenues due to corruption in turn influences the amount of funds that can be dedicated towards R&D, subsidies, investment and infrastructure that are essential for an emerging technology. Moreover, by distorting market mechanisms such as free competition, corrupt countries receive about 5% less investments, and the cost of doing business is on average 10% higher (OECD 2014).

This landscape factor can be analyzed by reviewing the estimated loss in public resources (percentage of GDP), mentioned canceled/never initiated entrepreneurial activity, and estimated impact on economic growth, as a result of corruption.

Landscape Factor 6: National Education System: Unequal Access to Education

The inclusion of *unequal access to education* as a landscape factor, is motivated by the central role of knowledge creation in relation to TIS system development. As put by Lundvall (1992, 1), “it is assumed that the most fundamental resource in the modern economy is knowledge and, accordingly, that the most important process is learning”. Lundvall (1992, 1) further emphasizes the “historical establishment” as well as the “institutional and cultural context”, in order to understand learning as a “socially embedded process”. In many developing countries, institutions have developed in a direction to primarily benefit the elite, which has contributed towards less inclusive economic and political institutions (Acemoglu and Robinson 2012). In wider system analyses (e.g. national innovation systems), unequal access to education in developing countries has been credited as one of the central aspects for explaining their “lack of technological congruence” (Soete, Verspagen, and Weel 2010, 1172).⁴⁶ In the systems of innovation literature, the national education system is commonly discussed in the wider NIS, which can be considered exogenous to the focal TIS and its functions. With the inequality component embedded in the national education systems in developing countries, it would be reasonable to treat it as landscape factor, rather than as an actor within the focal TIS. By including this landscape factor the aim is to bring clarity to the relationship between the national education system and technical innovation system in a developing country context.

As shown in the environmental awareness discussion (LF2), in the last decades, access to primary and secondary education has significantly improved in most of the developing world (see Fig. 3.4). Access to higher education, however, remains limited and restricted to a privileged elite in many developing countries, leaving a large portion of the population without access to higher education. The latest available data (2013) show that in low, lower middle and upper middle-income countries the total gross enrollment rates at the tertiary level are 8%, 22% and 35%, respectively (The World Bank 2016a). These tertiary enrollment rates can be compared to 74% in high-income countries (The World Bank 2016a).

The dual role of the education system, namely generating human capital (individual learning) while contributing to new knowledge, gives it a central role in the knowledge and learning environment (Edquist 2001). If a large part of the population is excluded from higher education, it may contribute to shortages in human capital and reduced learning to an extent that obstructs the focal TIS in

⁴⁶ Abramovitz introduced technological congruence in 1986 when discussing catching-up countries and absorptive capacity (Soete, Verspagen, and Weel 2010).

question.⁴⁷ A reduced possibility for generating awareness for the environment (LF2) and sustainable development is another potential consequence of low access to higher education (Lambrechts et al. 2013). Accordingly, the aim of including this landscape factor is to reveal its influence on knowledge development (F2a), adaptive capacity (F2b), entrepreneurial activities (F1) and other landscape factors. This landscape factor addresses questions such as how does unequal access to vocational and higher education influence human capacity and learning? And how does it influence the focal TIS? More specifically, in what way does unequal access to education influence the availability of researchers, engineers, project managers, and technical personnel? This landscape factor can be evaluated by mapping changes in access to higher education (post-secondary, vocational and tertiary education (including research), along with expressed mismatch (lack of trained personnel) by the industry of the technology in question, as a result of lack of access to quality education.

3.6 Interactions between Landscape Factors and Functions

A rationale for including the above mentioned landscape factors into the analysis is to understand the different pressure that they assert on the focal TIS in question. The suggested landscape factors can be nationally bound or transcend the national level. Economic growth and climate change are clearly landscape factors that operate across the national boundary. The performance of the national education system and the level of national corruption are nationally bound landscape factors. Armed conflicts or environmental awareness are relevant to analyze from a nationally bound perspective, i.e., how they influence the country under study, but may be transnational in nature. For example, the long lasting armed conflict in Colombia is predominately a domestic conflict, but it has involved neighboring countries, such as Venezuela and Ecuador, when armed groups have crossed the borders or displaced population has moved to these neighboring countries, for example. With the emergence of Internet and access to information across the national boundary, it can be debated whether domestic environmental awareness is linked with a changing global awareness, resulting from international environmental campaigns and movements.

Widening the analytical lens by systematically incorporating landscape factors to complement the TIS functional approach could assist in explaining the slow

⁴⁷ Note that in addition to universities, new knowledge is also created in research institutes and research oriented firms (Edquist 2001). R&D can be carried out within firms or academia, this has been classified as search and exploration, respectively (Soete, Verspagen, and Weel 2010). Lundvall (1992) has also emphasized learning through Doing, Using and Interacting (DUI) as opposed to the scientific approach.

diffusion of RETs in many developing countries. In addition, the objective is to determine if the landscape level influence is having a reinforcing or weakening effect on the incumbent system outcomes. In the MLP literature, landscape factors can create opportunities for change, while reinforcing factors do not contribute to innovation (Geels and Schot 2007).

The different landscape factors can induce reactions (disruptive or reinforcing) amongst different actors, e.g. incumbent regimes and/or policy makers. These reactions can influence the conditions for the focal TIS, or concrete changes in the TIS functions. Figure 3.5 provides examples of potential reactions induced by the selected landscape factors.

Figure 3.5 Examples of Influence from the Landscape Level

Source: Author

Note: This figure draws upon the compilation of interdisciplinary literature discussed in this chapter.

It is important to note that the landscape factors are macro-level factors operating outside the focal TIS, and do not exclusively influence specific technology sectors. Instead, the landscape level influence should be seen as an overarching umbrella, which can produce potential spillover effects that can prove conducive or impeding for a specific technology. The previous section, discussed the potential influence that the proposed landscape factors can have on TIS functions from a theoretical perspective. Based on these arguments, Table 3.3 provides a summary of the

potential influence that different landscape factors may pose on specific TIS functions. Table 3.3 is not suggested to be an exhaustive list of potential influence, but rather an initial guide for future empirical studies that opt to include the landscape factor influence into the analysis.

The landscape factor-induced influence on TIS functions, could then initiate reinforcing actions between different functions, providing positive feedback loops. These feedback loops between the functions can lead to a positive momentum that ultimately improves the performance of the system as a whole.⁴⁸ The feedback loops between functions have been covered in previous literature and will not be discussed further in this chapter (S. Jacobsson and Bergek 2004; S. Jacobsson and Bergek 2006; e.g., Hekkert et al. 2007). Instead, examples of possible reinforced influence between landscape factors will be discussed below (see Fig. 3.6).

Table 3.3 Possible Landscape Factor Influence on Specific System Functions

		Functions							
		Entrepreneurial Activities	Knowledge Development	Adaptive Capacity	Knowledge Diffusion	Guidance of the Search	Market Formation	Resource Mobilization	Creation of Legitimacy
Landscape Factors	Economic Growth							✓	✓
	Environmental Awareness				✓				✓
	Climate Change					✓		✓	✓
	Armed Conflicts	✓					✓	✓	
	National Corruption	✓						✓	
	Unequal Access to Education	✓	✓	✓	✓				

Source: Author (based on findings discussed in this chapter)

Note: Black check marks indicate possible interaction

Landscape Factors Reinforcing Effects

While the main focus of this chapter is on the influence that landscape factors may have on a focal TIS and its functions, evidence from existing literature suggests that reinforcing and weakening influence is occurring between landscape factors. The reactions or activities generated by one landscape factor may have reinforcing or weakening influence on another landscape factor. A non-exhaustive summary of possible influence between landscape factors is displayed in Figure 3.6.

⁴⁸ Note that negative feedback loops are also possible, which could instead limit growth.

In this chapter, the potential influence of the individual landscape factors on TIS functions has been emphasized. As it follows, the landscape factor to landscape factor (LF- LF) influence can contribute to shaping a more or less beneficial external landscape for technological innovation. Again, the selected landscape factors should be seen as a first step to systematically mapping out the wider context, and its weakening or reinforcing influence for a given focal TIS at an early formative stage. The focus of this chapter on environmental sustainability is reflected in the suggested framework. While landscape factors such as climate change or environmental awareness have been included with RETs in mind, other mitigating technologies, such as carbon capture and storage (CCS) or energy efficient technologies could also benefit from the suggestions made in this chapter. It is also the aspiration that the reflections made concerning the processes and landscape factors of the Technological Innovation System in developing countries will also benefit future empirical studies focused on technologies beyond the sustainability niche.

Figure 3.6 Reinforcing or Weakening Influence between Landscape Factors

Source: Author

Note: Generated reactions are displayed in the white box. Reinforcing influence is denoted by (+) and the weakening influence by (-).

3.7 Proposed Framework

The following section offers a summary of the suggestions provided in this chapter in the form of a proposed framework. Based on previous literature on the TIS approach, empirical studies in developing countries and lessons from the MLP,

four suggestions have been made. These suggestions show how the existing TIS framework can be elaborated upon to enhance its comprehensiveness and broaden the applicability of the framework to developing countries.

Table 3.4 Suggested Framework and Possible Indicators

System Function		Possible Indicators
F1.	Entrepreneurial Activities	Started and planned projects, experimentations and activities from incumbent actors for new technology
F2.a	Knowledge Development	Planned and ongoing research projects and patents filed; trends in publications relevant to the technology
F2.b	Creating Adaptive Capacity	Human (level of technical and higher education), organizational, and institutional capacity to receive new technology
F3.	Knowledge Diffusion	Number of workshops, conferences, or other forums (social media) organized about the new technology
F4.	Guidance of the Search	Expectations set by government or industry for new technology in terms of regulations and specific targets
F5.	Market Formation	Market entry assistance for new technologies (protected space ('nursing'), new environmental standards, tax exemptions, feed-in tariffs, etc.)
F6.a	Resource Mobilization (Government)	Resources allocated by government or industry towards R&D (Human Capacity) or subsidies for the new technology (financial).
F6.b	Resource Mobilization (International loans and grants)	Availability, size and type (human and/or financial) of international resource mobilization for new tech.
F7.a	Creation of Legitimacy/Advocacy coalition (formal lobbying)	Change in lobbying activities by formal and established lobbying groups with economic and political weight
F7.b	Creation of Legitimacy (informal lobbying)	Changes in public opinion, support and acceptance for new technology in social media
Landscape Factors (LF)		Possible Indicators¹
LF1.	Economic Growth	Changes in Gross Domestic Product (GDP), Global Economic Events
LF 2.	Environmental Awareness	Changes in frequency of online discussion forums, enrollment in environmental programs (higher education), changes in public awareness for RETs (e.g. national polls).
LF 3.	Climate Change	Changes in international and domestic commitment to RETs adoption; economic costs as a result of climate change
LF 4.	Armed Conflict	Cost of Conflict (% of Gov. Expenditure), number of canceled (or not initiated) entrepreneurial activities
LF 5.	National Corruption	Loss in public resources (% of GDP), canceled/not initiated entrepreneurial activity
LF 6.	National Education System: Unequal Access to Education	Access to upper secondary, vocational or higher education (including research), expressed mismatch from industry on available human capacity for new technology

Source: Expanded by author

Note: Indicators for unchanged functions reflect suggestions provided in the baseline function list by Hekkert et al. (2007). F2.b draws on van Alphen et al. (2008).

¹ All indicators include the perceived influence on functions and other landscape factors

Table 3.4 displays the added suggestions to complement the original list of functions by Hekkert et al. (2007), namely including creating adaptive capacity, a split of the resource mobilization function and a split in the creation of legitimacy/advocacy of coalition function. The landscape factors are added at the end of the list of functions and possible indicators to measure these factors are provided.

The fulfillment of system functions and the influence of landscape factors on system functions can be analyzed by a combination of a history event analysis, literature review and expert evaluations, i.e., structured and/or semi-structured interviews with experts in the field from the country under evaluation. In order to enhance the analytical comprehensiveness of the TIS framework, the findings of the external landscape assessment would be analyzed together with the findings from the Innovation System Function analysis.

3.8 Conclusions and Suggestions for Future Research

This chapter has discussed limitations of the TIS function approach and proposed a framework that both takes into consideration the wider context in which the focal TIS operates, while making adjustments to better account for the context found in many developing countries. While the changes to the previous function list were made with the consideration of developing countries, there are suggestions that also hold relevance for future studies in developed countries. For example, the split of the *creation of legitimacy* function that was made to better reflect changes in public support for renewable energy is also relevant in developed countries.

The landscape factors proposed in this chapter have been selected to hold special relevance in a developing country context, given the higher prevalence of corruption, inequality and unequal access to quality education often found in developing countries. This is not to say that certain landscape factors would not benefit future studies in developed countries. Landscape factors such as climate change, economic growth and the role of the national education system to reduce mismatch are aspects that could have an influence on incumbent regimes and focal TIS in developed countries as well. More generally, given the increased connectedness in the form of globalization and information technologies, countries may experience more rapid changes in landscape factors such as economic growth or environmental awareness today than a few decades ago. Thus, as a consequence, the inclusion of the potential effect of landscape factors on the TIS may be of even greater relevance.

The inclusion of the socio-technical landscape in the analysis of TIS proposed in this chapter should be seen as a first step to improve the analytical comprehensiveness of the TIS framework. The list of landscape factors proposed in this chapter must be empirically tested in developing countries (see Chapter 4

and 6) to determine its relevance for the formation of the focal TIS. Thus, a pragmatic approach to potential reductions and additions of the landscape analysis is to be preferred. Moreover, differentiating between what factors exclusively influence RETs and the TIS and what factors also apply to other technologies or the entire NIS, could add value to the approach and should be subject for future research.

Moreover, while a systematic landscape analysis arguably improves the comprehensiveness in explaining barriers and drivers of technological transitions, there are other aspects that are considered external to the focal TIS. For example, during the attempt to combine the TIS and MLP framework by Markard and Truffer (2008), they stress the influence of one niche-level technological innovation on another niche innovation. The potential effect of a complementary innovation system is a topic for future research. Overall, more work is needed to map the role that the wider context has on the development, diffusion and utilization of a new technology.

Finally, given the multitude of factors that can serve as a driver or barrier to RETs adoption, additional empirical studies determining the relative pertinence amongst factors is needed, in order for the TIS function approach not to become excessively complex and lose its practical applicability. It is important to find a balance between a comprehensive framework that takes into account the intricacy of the system and the factors that influence it, and a practical framework that can contribute to the decision making process. In Chapter 4, the framework is applied to a renewable energy technology in a developing country context, namely wind energy in Colombia.

Chapter 4. Identifying Barriers to Wind Energy Diffusion in Colombia: A Function Analysis of the Technological Innovation System and the Wider Context⁴⁹

4.1 Introduction

The need for diversifying the energy mix towards Renewable Energy Technologies (RETs) in developing countries is motivated by the pressure of reducing greenhouse gas emissions and supporting future energy security. By one estimate carbon dioxide emissions alone in developing countries will be roughly twice that of developed countries by 2040 (EIA 2013). Despite a large technical potential for renewable energies in many developing countries, the progress in adopting RETs and moving towards a diversified energy mix remains slow. In this chapter, Colombia's wind energy sector, which represents a largely unexploited energy source for the country, will be analyzed.

Colombia's energy mix is composed mostly of hydropower and thermoelectric plants that run with coal, diesel and natural gas. Given the ecological and human impact of large hydropower dams and of using non-renewable sources of energy, such as oil and coal, combined with diminishing reserves (oil is estimated to run out in 8 years and coal in 23), Colombia is in great need of diversifying its energy mix and transitioning towards renewable energy sources such as wind power (Vergara et al. 2010).

By utilizing only half of its technical wind energy potential, Colombia would be able to supply the entire country's demand for electricity (Pérez Bedoya and Osorio Osorio 2002). With a consistent presence of class seven winds (i.e. winds of 9 m/s at a height of 50 meters), Colombia is rated as one of the best countries in South America for generating electricity from wind energy. Moreover, wind in particular has been shown to serve as a good complementary energy source to existing hydro generation. In fact, higher average wind speeds have been found to coincide with droughts caused by El Niño⁵⁰, which highlights the role that wind

⁴⁹ An earlier version of this chapter has been published in the journal *Technology in Society* (Eds and 2017).

⁵⁰ In most of Colombia, El Niño, the warm phase of El Niño Southern Oscillation (ENSO) phenomenon, produces less than average precipitation and prolonged dry seasons, leading to droughts. La Niña, the cold phase of ENSO in turn is manifested through higher than

energy could play in assuring a reliable energy supply in Colombia (Vergara et al. 2010). However, after the first installed wind farm in 2003 (the Jeparachi project), the diffusion of wind energy has been at a standstill. Currently, Colombia has an installed capacity of wind power of only 19.5 MW, representing about 0.4 percent of the total technical potential. This chapter will focus on large-scale electricity generation, involving large wind power turbines.⁵¹

In order to conduct a comprehensive analysis of the barriers and drivers of wind energy in Colombia, this chapter applies an extended Technology Innovation System (TIS) function approach adapted for a developing country context in Chapter 3, while taking into account the influence of the wider context on the wind energy sector. By applying the proposed framework and methodology this chapter aims to answer the following research question.

What can explain the slow adoption of wind energy in Colombia?

In trying to answer the main research question, two sub-research questions are also posed:

1. What are the barriers within the functions of the technical innovation system in Colombia?
2. In what way does the wider context in Colombia influence the transition to wind energy and other Renewable Energy Technologies (RETs)?

The aim of this empirical chapter is also to contribute to the overall knowledge of applying the extended TIS function approach in a developing country context proposed in Chapter 3. Moreover, by including the wider contextual factors into the analysis, the aim is to contribute to the existing boundary debate⁵², i.e., what factors that should be considered exogenous vs. endogenous to the technological innovation system.⁵³

average precipitation and prolonged wet seasons, often leading to floods (Poveda, Álvarez, and Rueda 2011).

⁵¹ Large wind turbines normally range between 660 kW-1.8 MW capacity and are designed for large-scale electricity generation, which feeds into the electrical grid. Small wind turbines are designed for agricultural, residential or small businesses, and have a capacity between 50 kW-250 kW.

⁵² An elaborate discussion about the issue of delimiting the system is found in Chapter 6, comparing data from multitude studies, including the data and findings presented in this chapter.

⁵³ For a discussion concerning the difficulties of setting system boundaries see for example, Edquist, 2006.

4.2 Analytical Framework

4.2.1 Technological Innovation

The Technological Innovation System framework used in this chapter is based on the idea that existing technologies can be ‘locked-in’ in a current system and, by default, ‘locking out’ or blocking new technologies from entering the established market (Unruh 2000). A technology system should be seen as a complex compilation of actors, or put differently “as a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology” (Carlsson and Stankiewicz 1991, 94).

As its name implies, the Technological Innovation System (TIS) approach centers around a technology, instead of a geographical area as in the National Innovation System (NSI) approach (Freeman 1987; Lundvall 1992; Nelson 1993); an industrial sector, as is the case in the Sectoral Innovation System (SIS) approach (Breschi and Malerba 1997); or a specific region as in Regional Innovation Systems (RIS) (Cooke, Uranga, and Etxebarria 1997; Saxenian 1994). The TIS approach, which was introduced by Carlsson and Stankiewicz (1991), has been extensively adopted by scholars, as this approach is not limited to the study of technological aspects, but instead it captures the socio-technical processes which can influence the diffusion of technologies of socio-technical variation and their influence on the diffusion of technologies.⁵⁴

4.2.2 Functions of a Technological Innovation System

To understand the innovation system in detail it is important to analyze the activities of the different actors in the system. Studying the underlying processes that make up the innovation system improves the chances of identifying key characteristics of the system, including weaknesses and strengths (Lundvall et al. 2002; Hekkert et al. 2007). In the TIS literature these activities or processes are identified as ‘functions’. The function approach has been found to be effective in analyzing the essential elements of a technical system (Johnson and Jacobsson 2001). Numerous lists of system functions have been developed over the last decade, which indicates the fluidity of the TIS function approach and the need to adapt it to the particular system under study (Edquist 2005).⁵⁵

⁵⁴ See e.g., Hekkert et al. (2007); Jacobsson and Bergek (2004); Jacobsson and Johnson (2000); Suurs and Hekkert (2009).

⁵⁵ See e.g., Edquist (2005); Hekkert et al. (2007); Hillman et al. (2008); Johnson (2001); Suurs and Hekkert (2009).

4.2.3 Extended TIS function Approach and the Wider Context

The extended TIS function analysis used in this chapter was developed to address limitations of previous TIS frameworks.⁵⁶ The first concern with previous TIS frameworks expressed in the literature was that they have primarily been developed and tested empirically in developed countries (van Alphen, Hekkert, and van Sark 2008).

Secondly, previous TIS analyses have received criticism for not adequately considering the influence of the wider context, i.e. the context in which the TIS is embedded but that is not considered part of the focal TIS⁵⁷ (Coenen and Díaz López 2010; Markard and Truffer 2008; Geels, Hekkert, and Jacobsson 2008). The second limitation relates to the boundary debate, namely what factors outside the focal TIS may influence the performance of the TIS functions, i.e., acting as a driver or barrier for the new technology in question. Earlier literature has suggested that exogenous factors may have an even greater influence in a developing country context, due to the low level of development of the various functions of the innovation system found in many developing countries (Raven 2005).⁵⁸

The extended TIS framework used as baseline the functions list developed by Hekkert et al. (2007),⁵⁹ namely 1) entrepreneurial activities, 2) knowledge development, 3) knowledge diffusion, 4) guidance of the search, 5) market formation, 6) resource mobilization, and 7) creation of legitimacy. In order to better incorporate the developing country context, three changes were made to this list. The changes were: adding creating adaptive capacity⁶⁰, i.e. a country's ability to receive a new technology; splitting the resource mobilization and creation of

⁵⁶ See Chapter 3 for an extensive theoretical justification of the framework used for this chapter.

⁵⁷ One definition describes the focal TIS as “the realm where systematic interdependencies in a specific technological field play out” (Bergek et al. 2015, 52).

⁵⁸ Before the development, diffusion and utilization of a new technology is reached the TIS and its functions go through a formative (early) and growth stage (late) (Bergek, Jacobsson, and Sandén 2008).

⁵⁹ Hekkert et al. (2007) was chosen as a baseline functions' list, since it has been tested in various empirical studies and, thus, certain validity has been established (Negro, Hekkert, and Smits 2007; Negro and Hekkert 2008). See Hekkert et al. (2007) for a theoretical justification of the functions.

⁶⁰ Including adaptive capacity as a function is not novelty in the literature; it has been used in previous empirical studies in developing countries (see e.g. van Alphen, Hekkert, and van Sark 2008).

legitimacy functions to include a specific analysis of international resource mobilization and informal lobbying, i.e. public support and opinion.

The wider context factors of the extended TIS framework draw on the Multiple-Level Perspective (MLP) framework. The MLP framework, which can be used in the analysis of technological transitions, places more emphasis on the wider context than the TIS (Geels 2002). The ability of the MLP to take into account the incumbent actors (the ‘socio-technical regime’) and the wider context (the ‘socio-technical landscape’) has been considered an asset of the framework; while lacking in the TIS framework, according to Markard and Truffer (2008). Thus, this chapter addresses this criticism by systematically including the landscape analysis. Throughout the chapter, factors operating in the external context, i.e., outside the focal TIS system, will be referred to as *landscape factors*.

The following six Landscape Factors (LF) are included in the framework used for this study: Economic Growth, Environmental Awareness, Climate Change, Armed Conflicts, Corruption and National Education System (Unequal Access to Education). The landscape factors included in this study were carefully selected with a developing country context in mind and based on MLP and other cross-disciplinary literature, where they were suggested as potentially having reinforcing or disruptive influence on incumbent regimes or niche developments.⁶¹ Table 4.1 presents and describes the resulting functions and landscape factors of the extended TIS framework.

The extended TIS function approach used in this empirical should be seen as an attempt to improve the comprehensiveness of the analysis of barriers and drivers of technological change, but is not claimed to be a conclusive list of possible determinants. Rather an open and flexible approach is preferred (Lundvall 1992).

⁶¹ See for example *Economic Growth* (Geels 2013), *Environmental Awareness* (Smith, Voß, and Grin 2010), *Climate Change* (N. H. Stern 2007), *Armed Conflict* (Naudé 2007; Brück, Naudé, and Verwimp 2013), *National Corruption* (OECD 2014), *National Education System* (Edquist 2001).

Table 4.1 Description of Framework

System Functions (F)	Description
1. Entrepreneurial Activities	Activities/Interest shown by companies for new technology, e.g., started and planned projects
2a. Knowledge Development	Existing and new knowledge regarding the technology, e.g., research projects
2b. Creating Adaptive Capacity	Human, organizational and institutional capacity of a country to receive new technology
3. Knowledge Diffusion	How and to what extent knowledge about new tech. is shared among actors
4. Guidance of the Search	Actions by government or companies that affect expectations of new tech. (e.g., regulations and specific targets)
5. Market Formation	Specific mechanisms that facilitate entry of the new tech. to the energy market (e.g., tax exemptions, pricing policies)
6a. Resource Mobilization (Domestic)	Financial resources allocated by government or companies for new tech.
6b. Resource Mobilization (International)	Financial and technical assistance by international actors for new tech.
7a. Creation of Legitimacy (formal lobbying)	Lobbying activities affecting legitimacy and support for new tech. by established groups with economic and political weight
7b. Creation of Legitimacy (informal lobbying)	Activities affecting legitimacy and support for new tech. by the general public
Landscape Factors (LF)	Description
1. Economic Growth	How the strength or weakness of the country's economy may influence the adoption of new tech.
2. Environmental Awareness	How environmental awareness may create actions that influence transition towards new tech. (e.g., through pressure on incumbent actors to diversify)
3. Climate Change	How climate change may influence the transition to the new tech.
4. Armed Conflict	How armed conflicts may influence the adoption of the new tech. (e.g., through the impact on govt. expenditure, and/or canceled/ never initiated entrepreneurial activities in conflict areas)
5. Corruption	How corruption may affect transition of a new tech. (e.g., loss of financial resources)
6. Inequality: Unequal Access to Quality Education	How unequal access to quality education may influence adoption of new tech. (e.g., through limited human resources in areas with high technical potential for wind)

Source: Author, based on analysis and suggestions made in Chapter 3.

Note: Baseline function list before changes is based on Hekkert et al. (2007).

4.3 Methodology and Data

In order to answer the research questions, interviews and a history event analysis were carried out. The primary data to analyze the barriers and drivers (within functions and landscape factors) of the wind energy sector is gathered from structured and semi-structured interviews. The history event analysis aimed at providing a broader picture of changes related to the functions and landscape factors, as well as corroborating and complementing the interviews.

4.3.1 Expert Evaluations: Sampling and Analysis

Interviews were conducted in Colombia between April and June of 2014. The sampling targeted experts with extensive experience within wind energy and RETs in Colombia. A total of 16 leading experts were interviewed. The early formative stage of the wind sector in Colombia limits the amount of specialists that actively work within the sector, constraining the possibility for a larger sample size. This limitation was compensated by conducting a maximum variation sampling of a wide representation of experts that actively work within the field of wind energy and other renewable energy technologies in Colombia from a variety of groups including government agencies, energy generating companies (EGCs), research institutions (universities), and international development organizations.

For the structured part of the interviews, experts were asked to rate the performance of each function using the following Likert scale: very bad (1 point), bad (2), acceptable (3), good (4), very good (5 points), and not applicable (N/A). Experts were also asked to rate the perceived influence of each landscape factor on the TIS functions as: not important (1 point), little importance (2), important (3), very important (4), extremely important (5 points), and not applicable (N/A).

To allow experts to elaborate on their answers, the interviews also included a semi-structured part (Somekh and Lewin 2005). The semi-structured interviews followed a prepared topic guide with a list of open-ended questions relating to all TIS functions and landscape factors included in the framework (Table 4.1).⁶² See Appendix I for detailed information concerning the forms used and questions posed during the interviews.

4.3.2 History Event Analysis

The history event analysis was conducted through a combination of media content analysis, existing databases and literature review. The data for the media content

⁶² All quotes in this chapter are translated from Spanish by author.

analysis was collected using the Lexis Nexis© database in 2014, including major Colombian and Latin American mainstream and business newspapers.⁶³ The search words used were wind energy, Colombia and Projects. The history event analysis was constrained by unavailability of data.

4.4 The Colombian Energy Sector

This section provides an overview of the Colombian energy sector, including current energy supply, existing actors and structure of the energy sector.

4.4.1 Structure and Actors in the Energy Sector

In 1994, a new law was passed that initiated the restructuring of the Colombian energy sector. The restructuring involved allowing participation of private companies in the energy sector and dividing the electricity production chain into four activities: generation, transmission, commercialization, and distribution (Coviello, Gollán, and Pérez 2012). Regulated natural monopolies control transmission and distribution, while private companies and public enterprises are responsible for generation and commercialization.⁶⁴ While a multitude of energy companies exist in Colombia, three large companies, are responsible for 72% of all electricity generation: Empresas Públicas de Medellín (EPM), EMGESA and ISAGEN, (ACOLGEN 2015). Several public institutions are responsible for planning of the energy sector that serves the National Interconnected System (SIN, for its acronym in Spanish) and Non-Interconnected Zones (ZNI, for its acronym in Spanish) (see Fig. 4.1).⁶⁵

⁶³ Newspapers used in analysis include: El Espectador, El Colombiano, La República, Portafolio, Dinero, Esmerk Colombia News, News Bites - Latin America: Colombia, Noticias Financieras, Noticias Financieras Premium Publications, Troubled Company Reporter - Latin America, Webnews-Spanish, ABC, Reforma.

⁶⁴ Ownership of energy companies are classified as private, public or mixed. At the end of 2015 there were 56 electricity generators, 12 transmission companies, 31 grid operators and 93 commercialization companies registered in the SIN (National Interconnected System) (XM 2015). Examples of distribution companies include Codensa S.A. E.S.P., Empresa de Energía de Boyacá S.A. E.S.P., Empresas Públicas de Medellín S.A. E.S.P.

⁶⁵ The National Interconnected System (SIN) is the nationally integrated power grid and supplies 96% of the Colombian population with electricity but only spreads over one third of the country. The remaining two thirds making up 4% of the population are known as remote Non-Interconnected Zones (ZNI) (The World Bank 2004).

Figure 4.1 Planning of the Energy Sector – Responsible Organizations

Source: MME and IDB (2010) (Modifications made by author: DNP and COLCIENCIA added).

4.4.2 Energy Demand and Supply in Colombia

Energy demand in Colombia has risen steadily in the past decades. Between 1990 and 2013 the total demand for electricity alone nearly doubled, increasing from 28.85 to 55.73 Twh per year (IEA 2016a). The energy mix in Colombia has maintained a similar composition for the past 30 years with almost 80% of its electricity generation produced by hydropower and almost 20% by thermoelectric (García et al. 2013). The participation of non-conventional renewable sources of energy is less than 1% produced by biomass and wind power, and 4.3% by small hydropower (<20MW). In 2005, 81.26% of the electricity was generated by hydropower, 18.64% by thermoelectric and 0.10% by wind (XM 2005). In 2012, 67% of electricity was generated by hydropower (of which 65% was large hydro, and 2% small hydro), and 32.7% by thermoelectric, 0.14% was co-generation and 0.13% wind power (García et al. 2013). In 2014, hydropower accounted for 65.5% of energy generation, thermoelectric for 28.6%. In 2015, the share of thermoelectric generation increased to 31%, while hydropower reduced to 63.8% (XM 2015). In short, a trend of increasing share of thermoelectric generation has been seen in the past decade, intensified in years of water scarcity where deficiencies in hydropower generation are normally compensated with increased thermoelectric generation (García et al. 2013; XM 2015).

The consequence of augmented electricity demand being largely covered by increased thermoelectric generation has resulted in a continuous rise in Colombia's greenhouse gas emissions from fuel combustion, from an annual 45.78 Mt of CO₂ in 1990 to 72.50 Mt CO₂ in 2014 (IEA 2016a). Based on the country's generation and transmission expansion plan for 2011-2025, it is projected that in the period of 2011-2025 Carbon Dioxide Equivalent (CO₂e) emissions from energy production will double⁶⁶ (García et al. 2013). Meanwhile, the diffusion of renewable energies, including wind, geo-thermal and small hydro has been slow or stagnant. The augmented demand for electricity, generated by economic growth as well as urban migration will, unless a diversification of the energy mix occurs, further increase energy sector-related greenhouse gas emissions.

4.4.3 Renewable Energies

Together, renewable energies such as wind, geo-thermal and small hydroelectric generation make up about 5 percent of the total energy generation in Colombia, 0.4 percent of which is derived from wind energy (MRI, UNC, and NUMARK 2010). The majority of renewable energy originates from small hydro, which by Colombian law is only fully considered as a renewable source when below 10 MW in size. Based on this law, Colombia generates about 169MW from renewable small hydro. Slightly larger hydroelectric generation (size 10-20 MW) contributes with 296 MW to the national grid. Biomass and wind energy generate a very small amount of renewable electricity, approximately 32MW and 20MW respectively (MRI, UNC, and NUMARK 2010).

4.4.4 High Technical Potential for Wind Energy

Several areas of Colombia hold great technical potential for wind energy generation. La Guajira in the north of Colombia has some of the best wind potentials in South America. The trade winds in this part of the country blow nearly all throughout the year, with an average wind speed of 9.8 m/s. In addition to La Guajira, other regions, including the island groups of San Andrés and Providencia, along with the departments of Santander, Norte de Santander, Boyacá, Valle del Cauca, Risaralda and Huila also hold potential for wind power.

In 2002, Colombia, in collaboration with the World Bank and Empresas Públicas de Medellín (EPM) installed its first wind park in La Guajira, located on the northeastern Caribbean coast. The wind park, which was named Jepírachi, meaning northeast winds in the local indigenous language Wayuunaiki, consists of fifteen 1.3 MW wind turbines, totaling 19.5 MW for the entire park. The park, which

⁶⁶ This estimate includes projected energy generation from biomass, natural gas, liquid combustion and mineral coal.

became fully commercially operational in 2004, was instigated under the Clean Development Mechanism (CDM)⁶⁷, and was considered a first step in reducing the GHG emissions in Colombia. However, since the development of Jepirachi, there have been no new wind parks installed in the country.

4.5 Analysis of the Technical Innovation System and Landscape Factors in Colombia

The following section uses the extended TIS framework to examine the status of functions and the perceived importance of landscape factors in influencing wind energy adoption in Colombia. The analysis will reveal the current relative strength and discrepancies in the innovation system. The section begins by depicting the results from the structured interviews, which will provide an initial indication of the perceived strength and weakness of functions, along with the perceived importance of the landscape factors. This is followed by a more in-depth analysis of each function and landscape factor (including the direction of the influence, i.e., positive or negative), based on the semi-structured interviews and history event analysis.

4.5.1 Structured Interview Results

Table 4.2 provides a computed average of the function fulfillment and perceived importance of landscape factors in Colombia based on the structured interviews. The results reveal an overall low fulfillment of the functions, with scores ranging between 1.7 and 2.6, out of a maximum of 5 ('very good'). The small difference between function average scores limits the inference of clear indications of significantly better and worse performing functions. Looking at the outcome from an individual basis, no functions received the rating 'very good' (5 points) from any expert. The only functions receiving the rating 'good' (4 points) were entrepreneurial activities, international resource mobilization, adaptive capacity and knowledge diffusion; the former two receiving 'good' by only one expert from the government and the latter two receiving the rate of 'good' by two different experts from EGCs.

Government resource mobilization in Colombia was considered the lowest performing function, with an average score between 'very bad' (1) and 'bad' (2), while entrepreneurial activities and adaptive capacity demonstrate a slight advantage against the other functions. The explanations behind these results will be further elaborated in following sections.

⁶⁷ The Clean Development Mechanism (CDM) is specified under Article 12 of the Kyoto Protocol to support projects aiming at reducing carbon emissions (UNFCCC 2014).

Table 4.2 Structured Interview Outcome - Functions and Landscape Factors

Technological Functions	Mean Score
F1. Entrepreneurial Activities	2.6
F2.a. Knowledge Development	2.3
F2.b. Adaptive Capacity	2.6
F3. Knowledge Diffusion	2.3
F4. Guidance of the Search	2.0
F5. Market Formation	2.2
F6.a. Resource Mobilization (Government)	1.7
F6.b. Resource Mobilization (International loans and grants)	2.1
F7.a. Creation of Legitimacy/Advocacy coalition (formal	1.8
F7.b. Creation of Legitimacy (informal lobbying)	1.8
Landscape Factors	Mean Score
LF1. Economic Growth	3.7
LF2. Environmental Awareness	3.3
LF3. Climate Change	3.8
LF4. Violence and Conflict	3.1
LF5. Corruption	3.8
LF6. Inequality: Unequal Access to Quality Education	3.6

Note: Based on Likert Scale (1-5), where the score 1 indicate the weakest performance of a function and 5 the highest. For the landscape factors, 1 indicates the lowest importance in terms of their influence on the functions and 5 represents the highest perceived influence. The results depicted for both functions and landscape factors are the combined averages based on all actors (government departments, EGCs, and research institutions (universities) and international organizations) in Colombia.

Similarly to the functions, small differences resulted in the mean scores between the six landscape factors. Corruption and climate change showed a slightly higher level of importance than the other landscape factors, with a mean closer to ‘very important’. Violence and conflict received the lowest average score in comparison, however they were also considered ‘important’ (3.1). An interesting contrast in how the different actors perceive the influence of the landscape factors can be observed in the data, as shown in Figure 4.2. For example, interviewees from EGCs gave low average scores across several landscape factors. In particular, the lower perceived importance of climate change amongst EGCs stands out, as compared to other actors. Another notable variation is the consistently higher emphasis of landscape factor influence on functions expressed by experts from research institutes. One plausible explanation for this variation could be that the often-slower change and influence generated by the landscape level is revealed in wider longitudinal studies, which may be considered to a lesser degree by EGCs. Regardless of the cause for the discrepancy, the variation suggests that information

regarding landscape factors influence is not sufficiently shared amongst actors. A limited knowledge sharing and the consequential mismatch in describing the barriers and drivers of wind energy and other RETs could contribute to the slow diffusion in Colombia.

Figure 4.2 Differences between Actors’ Responses Regarding Landscape Factors Influence on Adoption and Diffusion of Wind Power in Colombia

Note: Scores are accumulated averages of all experts within each actor category.

4.5.2 Function Analysis

Function 1: Entrepreneurial Activities

As noted earlier, despite the large technical potential for wind, Colombia has not built any additional wind farms since installing Jepirachi in 2003. Initiatives for additional wind parks first began to be frequently mentioned again as an alternative power source in 2009 (see Fig. 4.3). The media content analysis showed that 2009 was the year with the highest number of companies mentioning their interest to invest in wind energy projects.

In August of 2009, EPM made investment plans of US\$ 2.5 billion over the next four years, and mentioned new wind farms as part of the investment. Moreover, due to Colombia’s large technical capacity for wind energy, international companies from Argentina (Impsa) and Spain (Grupo Endesa) declared in 2009

their interest for investing in wind energy in Colombia. Collaboration between Ecopetrol, the Colombian state-owned oil company, and the Institute for the Development of Science and Technology (Colciencias) has committed investments of US\$ 3.68 million for the development of ten energy projects, one of which involves plans for a small scale wind power project (Portafolio 2010a).

Figure 4.3 Planned Entrepreneurial Activities by Energy Companies to Invest in Wind Project

Source: Media content analysis through Lexis Nexis.

The most concrete and promising initiative is a wind farm in Uribia, La Guajira, currently being developed by ISAGEN and the local indigenous population Wayuu. The project, which received initial approval by the regional authorities in early 2010 will involve twenty 1.5 MW turbines. The wind farm will be divided into plants, where ISAGEN will be in charge of 20 MW of generation and Wayuu communities of 12 MW (Portafolio 2010b). Overall, despite the stalemate of wind energy projects in Colombia since 2003, the increase of mentioned plans in media by Colombian and international energy companies still provides a positive indication of the future of wind energy in the country.

However, among the incumbent energy generator companies, which are still today heavily invested in hydroelectric generation, the realization of finalized wind parks in Colombia is moving at a very slow pace. The interviews revealed that there is a persisting lack of knowledge for the potential benefits of wind energy, along with a concern for how wind energy may impact the existing energy system, which can

explain the slow pace (Chapter 5). Experts explained that knowledge diffusion (F3) is hampered by the limited partnerships between the EGCs and academia. Also, guidance from the government (F4) encouraging collaboration between various actors around wind energy is expressed as largely absent.

The interviews also revealed another possible explanation for the limited entrepreneurial activities around wind energy, namely the operational difficulties experienced with Colombia's first wind park. Jepírachi was not primarily designed as a learning project, which resulted in that as soon as it experienced problems, it did not receive sufficient funding or maintenance, which in turn provided bad publicity for wind energy as an alternative energy source (negatively affecting legitimacy – F7). The current energy market (F5) in Colombia rewards reliability, and given the lack of knowledge about wind, combined with the negative experiences from Jepírachi (see also functions 2a and 6b), wind energy is being undermined as a viable energy alternative when compared to well tested technologies such as hydro and thermoelectric.

Finally, insufficient infrastructure, in terms of energy grids was expressed in the interviews as another aspect that slows down the implementation of new wind energy projects. The installation of energy grids, which is the responsibility of the government agency Mining and Energy Planning Unit (*Unidad de Planeación Minero Energética* - UPME), has left the regions with high potential for wind energy, such as La Guajira, unconnected or poorly connected to the national grid (SIN). Without an electric grid in place, the cost would fall on the energy companies, which could serve as a deterrent for entrepreneurial activities.

Function 2a: Knowledge Development

As noted by experts from research institutes, while Jepírachi experienced many complications for the first 3 years of operation, EPM hired wind energy experts to study the wind park where lessons for future projects could be extracted. However, when it comes to the technology, Colombia has not made the necessary investments to develop its own large wind turbines and would have to adopt such technology from other countries. The knowledge base and the political support to create the industrial base for developing large turbines for wind parks does not currently exist in Colombia. Interviews with experts from several research institutes, however, confirmed ongoing innovative research and projects, where small-size wind turbines are being developed. In recent years, collaboration between several universities has emerged where different applications of both solar and wind energy are being tested and analyzed. This collaborative research between universities has contributed to developing new knowledge about wind, including the technical potential for wind power across Colombia. Moreover, as will be discussed under *landscape factor 4 (armed conflicts)*, military funding has been granted to universities to develop small sized RETs solutions for military personnel, which has influenced the directionality of knowledge creation for

technological innovation. Consequently, as experts have highlighted, technological innovations are limited to smaller sized solutions for wind energy and do not involve large wind turbines suitable for wind parks, which is the focus of this study.

Additional knowledge development activities include ongoing efforts to analyze the complementarity of resources in Colombia, and how to diversify from a hydro-dominated energy mix drawing on studies from other countries with similar energy supply conditions, such as Norway. Also, initial studies mapping wind resources in Colombia have already been completed, although EGCs are asking government for more detailed maps that would facilitate the planning for future investments, including wind energy cost-benefit analyses. Since previous wind mapping studies have been conducted by private entities, the government loses much of this information, which contributes to the knowledge gap among policy makers concerning the potential of wind generation.

Experts from EGCs stress that one essential knowledge gap that exists in the government is the lack of recognition of the complementary potential of wind for hydropower, i.e. when there is little water there are usually significant levels of wind, and vice versa. An important step to realizing this potential is to change the existing method for calculating how energy can be provided to the system by wind power, as the current system of calculating reliability is based on incumbent regimes, i.e., hydro and thermoelectric.

Function 2b: Creating Adaptive Capacity

Adaptive capacity, or the ability of a country to receive a new technology, can be explored by looking at the human, organizational and institutional capacity of the country. In Colombia in terms of human capacity, the country has a high degree of qualified engineers, although engineers specialized in wind energy are few. Interviews with universities revealed a concern for the lack of specialized higher programs in RETs, which forces many researchers to pursue their Master's and Doctoral degrees in other countries, primarily Europe and the USA, where they often remain after completion of their studies. At the same time, research institutes confirm a slight increase in the return of Colombian researchers and a positive trend for new research and knowledge concerning wind and other RETs. A specific concern in terms of human capacity, revealed in the interviews, is the limited technical personnel with the skills necessary for installing and maintaining a wind park, especially in remote rural areas where wind parks could be installed. The lack of technical personnel in rural areas also relates to the high level of urban-rural inequality in Colombia, which will be further discussed under landscape factor 6 (unequal access to quality education).

The capacity of the government to make decisions and take action for new initiatives (i.e., organization capacity) is unanimously described amongst EGCs,

research institutes, governmental agencies and international organizations as slow and inefficient. This is being manifested in the limited capacity of the central government to provide a clear direction for regional actors. In addition, there are seven different entities within the central government involved in the energy sector, and thus the actions (or inaction) of one may affect the diffusion of wind energy. For example, the Ministry of Finance may not provide sufficient funds for wind energy or the Ministry of Environment may block its progress due to protection of birds or natural protected areas. This slow decision making and implementation of new initiatives can be described as coordination failure amongst central government entities as well as between central government entities and regional actors. The latter can be seen as consequence of decentralization policies in Colombia, which demands good coordination between central and regional government entities, while relying on regional government's ability to implement policies.

The organizational capacity is further influenced by short-term contracts and rotation of personnel in government agencies, which is a result of the existing contracting scheme where people remain in their roles for 6-8 months. This turnover of people that work in a specific area such as RETs creates a strain on institutional effectiveness, in the form of low productivity during the training period of new personnel, periods of absence of personnel in-between contracts, and a lack of institutional memory.

Moreover, the Colombian institutional culture was described by study participants as reactive, i.e. the country does not usually plan ahead and preparing to receive a new technology by, for example training technicians, specialized engineers and projects managers; instead once a new technology arrives the country reacts to the needs that come with the technology. This in turn creates a 'chicken and egg' situation where the government will not make the necessary investments in preparing the country for the technology until it has arrived, and where investors may hesitate to invest due to apparent deficiencies in adaptive capacity. An explanation for the institutional inadequacy has been described as a general lack of awareness (LF 2) in the government for the role of wind energy. As a Colombian researcher puts it, "I do not think that the awareness of the Government for the importance of wind energy is enough to be able to say, '[this is important], let's bet on this and let's go for it', and thus, there is no pressure for action from the institutions that have the power to make it happen".

Function 3: Knowledge Diffusion

The level of knowledge dissemination concerning wind energy is perceived differently amongst different actors. While staff from EGCs describes limited to non-existent knowledge diffusion, research institutions and government agencies referred to a variety of existing dissemination activities for wind energy and other RETs. That is, while certain knowledge exchange is occurring amongst

government departments, international organizations and research institutes, the information appears not to be reaching some of the EGCs. The lack of clear policy directives creates limited incentives to bring the knowledge diffusion from a theoretical discussion to practical implementation with EGCs. The new RETs energy law passed by Congress in May 2014, which will be further discussed under function 4 (Guidance of the Search), may contribute to an increased interaction between different actors.

Despite the low knowledge diffusion found in EGC, one company described how they are actively trying to break existing misconceptions regarding wind energy, and sharing the findings from internal research projects with other energy companies and government agencies. Representatives from the government declare that while some knowledge diffusion exists in government, the exchange of knowledge does not reach all the essential departments of the government. An overall expansion of knowledge exchange between different actors is needed in Colombia, which could turn into important feedback loops for the functions. For example, an enhanced knowledge exchange about the benefits of wind energy, such as reducing the risk of energy shortages during El Niño, could contribute to the legitimacy of wind energy, and this in turn could improve resource mobilization and/or guidance of the search.

Another reiterated aspect of knowledge diffusion by experts was the need of introducing knowledge generation for wind energy and other RETs in education, as early as early childhood education, in order to increase overall environmental awareness. This would include education about sustainability, in which RETs is an integral part of, among the population at large, and in turn enable for a higher legitimacy for wind energy and other RETs.

Function 4: Guidance of the Search

All interviewees agreed with the need for the government to provide clear long-term targets, which specify the desired percentage of wind in the energy mix, including a date for when to reach this objective. The government has increasingly paid attention to environmental issues, including the need for a diversified energy mix, but specific guidance on targets remains vague. Environmental sustainability was first mentioned in the National Development Plan, which is prepared by each president, in 2006 during the presidency of Álvaro Uribe. Since then environmental sustainability has received increased priority in national objectives. The 2014 Renewable Energy (RE) law can be considered a positive step towards mainstreaming RETs into the existing energy mix. However, even in the law, the objectives remain vague. For instance, as explained by a representative of the planning department (DNP), there is a national target that by 2025 10% of the energy mix should come from renewable energy. Yet, targets do not specify how much generation should originate from which renewable energy source, e.g., wind, solar or geothermal. The lack of clear targets and specific incentives for wind

energy could hamper investments in this source of energy.

Representatives from EGCs confirm, for example, that while there are few subsidies for importing equipment, there are no subsidies for wind energy generators. Representatives from EGCs also emphasized the need for government support to construct the required infrastructure that would connect zones with high potential for wind to the national grid. Finally, government support that would mediate in the negotiations in areas with large indigenous communities would greatly facilitate wind energy projects. According to one EGC, the installment of one tower for measuring wind resources in La Guajira took 3 years, due to negotiations with the indigenous populations. The government thus may have to take a more active role in supporting wind energy in its initial stage.

Since the current energy system is designed to benefit hydro and thermoelectric generation, even with the new RE law in place, further reforms are needed to allow for the new law to take effect. Colombia takes pride in regulatory stability and the new law provides responsibilities to seven different institutions to implement a new policy. With this institutional rigidity and bureaucracy a slow implementation of the new regulation is most likely to be expected. However, the recent intention of the Colombian government to join the Organization for Economic Co-operation and Development (OECD) would commit the country to sustainable growth and to setting clear goals and targets for how to achieve this, which may speed up the process for change in Colombia (OECD 2013).

Function 5: Market Formation

Market incentives for environmentally friendly products have increased over the last decade. The new RE law proposes tax exemptions for import of RETs equipment, along with an exemption of the added value tax (VAT), and potentially other subsidies for initial investments. A fifteen-year tax exemption for energy sales from wind energy was already introduced in 2002. The tax exemption can be acquired through Clean Development Mechanism certificates, which provide supplementary income for the generating company (Dyner, Olaya, and Franco 2011). However, this tax exemption, which includes the conditionality to reinvest 50% of the obtained subsidy into social programs, has proven insufficient to incentivize new investments in wind power.

Actors express a culture in Colombia that holds reluctance towards supporting direct market incentives, which deems it unlikely that tools such as feed-in tariffs will be introduced for wind energy. This attitude is particularly of concern due to the dominating hydropower sector where the cost of a kWh of energy in Colombia is very low. Thus, without direct market incentives, wind energy would have to compete freely on the market with the dominant hydro and thermoelectric competitors, which could negatively affect market entry for wind.

The comparative advantage for wind, compared to large hydro and thermoelectric power generation, is its lower environmental and social impact. The larger generating companies have recognized the increased resistance by communities to new hydro projects, and they are as a result increasingly considering wind energy as a viable investment. Thus, including the social and environmental costs in the cost-benefit calculations would enhance the chances for wind energy to enter the market.

Function 6a: Resource Mobilization (Government)

There is an expressed need for additional resources for Research and Development (R&D) to bridge the persisting knowledge gaps in regards to wind. The R&D spending (% of GDP) has remained low, with only a minor increase from 0.11-0.18 percentage of GDP between 2000-2011. This can be compared with the OECD average of 2.39 percentage of GDP (The World Bank 2016c). Moreover, from the government resources allocated, a large part (about 70%) is lost to paying salaries at COLCIENCIAS, which is the organization responsible for distributing money for research in Colombia. Also, about half of the budget available for research is allocated to scholarships for PhD students abroad. As previously discussed, many Colombian doctoral students choose to stay in Europe or the USA, which contributes to a brain drain in Colombia. However, a new proposal by the government to utilize 10% of profits from oil towards research in Colombia could significantly strengthen the countries' R&D capabilities. The usefulness of this initiative is however still to be seen, which will depend on existing actors and the institutional and organizational capacity of Colombia (see function 2B) to make effective use of these additional resources.

There are already research groups in several universities that are working with wind energy and other RETs that would greatly benefit from additional resources. Lack of resources for specific research activities such as mapping the costs and benefits for wind energy, including energy demand and social and environmental aspects, was raised as an issue in the interviews. Another suggested government sponsored activity was to improve the connection or research collaboration between government, EGCs and universities (F3) to improve the transfer of knowledge between the different actors.

Building of transmission lines, i.e. extending the national grid that today only covers about half of the country's territory is a priority that requires government resources and engagement. The current process to receive approval to build transmissions involves rigid requirements where projects must prove the demand and reliability for wind energy. The benefits of emerging technologies are often harder to ensure, and thus many new transmission line projects that would connect to RETs receive a negative verdict, resulting in transmission lines never being built.

Function 6b: International Resource Mobilization

There is a large global interest in wind energy, e.g. China just reached 7% of its total generation from wind energy, earning it first place in the world before Germany and the United States (GWEC 2014). The role of wind energy in reducing dependence on fossil fuels has engaged corporations, multilateral organizations and other international groups to promote investments in wind. Multilateral organizations such as the World Bank and the Inter-American Development Bank (IDB) have provided the Colombian government with both capacity building, through empirical studies on wind energy, and with financial support for energy projects.⁶⁸ Colombia is the second largest recipient in Latin America and the Caribbean of financing for energy projects from IDB, with US\$ 3.029 billion disbursed for energy projects since the early 1960s (IDB 2015a).

However, in part due to previous low level of interest by the government and lack of a central entity that can drive these efforts through, the investments do not reach the market in the form of wind projects, which have resulted in lost opportunities. Thus, capital for investments is available but sufficient government guidance (F4) is missing. The hope, expressed by several interviewees, is that the new RE law will not only provide improved incentives for wind energy but also promote financing of future projects. In fact, the new law contemplates the creation of a fund that can receive resources from private and public entities and multilateral organizations to develop infrastructure and promote wind energy and other RETs. This fund would be supervised by the Mines and Energy Ministry and managed by a leasing company.

Some hesitance in regard to international financing was expressed in the expert evaluations, which is a result of previous poor experiences and fear of debt. For example, the financing of Jepirachi, which was financed by a loan from the World Bank, experienced several simultaneous problems. The project's cost was estimated at US\$ 21 million but ended up being much more expensive because there was a sharp rise in the value of the US dollar, which went from about 1,900 Colombian pesos to 2,500 pesos per dollar shortly after the project had begun. In addition, bonds to the Clean Development Mechanism (CDM) were sold for US\$ 4/ton of CO₂e by the Colombian government; the next day the price for bonds rose to US\$ 21/ton of CO₂e. The poor financing experience both raised the hesitance for international financing, while also painted a dim picture for wind energy in terms of price as compared with hydro. That said, Colombia is dependent on receiving international financing for future projects and EGCs do not see much difficulty in obtaining the necessary capital once the right incentives for investment are in place.

⁶⁸ (See e.g. Vergara et al. 2010; IDB 2015b)

Function 7a: Creation of Legitimacy (Formal lobbying)

As mentioned above about the Colombian energy sector, three very large companies, all of which are heavily invested in hydropower, dominate the energy generation in Colombia (EMGESA, EPM and ISAGEN). These three companies, which together with 14 other companies make up 100% of hydro-generation in Colombia and 52% of thermoelectric generation in the country, have formed a lobbying association called ACOLGEN.

An association of thermoelectric companies (ANDEG), created in 2010, lobbies for improved conditions for thermoelectric energy generation. According to actors from within the hydro dominating generators, thermoelectric companies generally resist new technologies such as wind energy, given that it would deem thermoelectric energy production both environmentally and price-wise inferior to the new technology.

Support for wind energy is interestingly found amongst the large hydro generating companies, which can be largely explained by the environmental and social constraints of hydro, combined with complementary qualities of wind for hydro generation. The dominant actors within ACOLGEN, that is, EPM, EMGESA and ISAGEN, for which hydro generation makes up 85%, 86% and 91% respectively of their total generation, are a group with regulatory weight, i.e., with the power to influence government decisions (ACOLGEN 2015). The semi-structured interviews conducted with representatives from these companies revealed that they have begun to lobby for improved conditions for wind energy. They mentioned having recently raised the possibility to open a sub-association to ACOLGEN that would solely focus on the promotion of wind energy.

However, cautionary voices from both government agencies and research institutes emphasize the heavy investment of ACOLGEN members in hydropower, and their probable reluctance to rapid changes in energy generation. In other words, Colombia is experiencing a significant hydro lock-in. Due to the existing knowledge gap in essential government agencies with regards to the potential of wind energy in Colombia, formal and/or informal lobbying activities (F7A and B) will be important to unlock the current path and allow for wind energy to be diffused.

Function 7b: Creation of Legitimacy (Informal lobbying)

Government agencies recognized that there is limited public focus on RETs, and thus limited informal lobbying for the issue, but there is a trend of increased attention to environmental issues. In addition, some scattered informal lobbying is also taking place in the form of individual journal and news articles where wind and other RETs are being promoted. Government representatives explain that the

limited public focus on RETs is in part due to larger concerns such as poverty, violence, as well as other environmental issues such as that of mining. One EGC confirms that a more active informal lobbying has emerged, although with less regulatory strength than the formal lobbying. As described by an ISAGEN representative, “there are a series of people on the environmental side, and a series of people and companies promoting and selling RETs but they do not have the strength or market power to carry it through.” Accounts from smaller energy companies confirm this picture, that RETs and especially wind energy is being promoted in news articles and research documents but in an unorganized manner.

Perhaps the most positive trend in informal lobbying for wind energy and other RETs can be found in universities. There is a general change in mindset and increasing attention given to RETs in universities. As a professor leading a RETs research group at a major Colombian university explains, “If you would have come [to a university like this one] 5 years ago, we did not talk about RETs, but today we have a research group that focuses specifically on this topic”. Research groups and interdisciplinary teams working on RETs are growing in size and focus, including engineers and social scientists, many of whom are generating and disseminating knowledge to the public and government officials concerning wind and other RETs, and thereby increasing the critical mass necessary for informal lobbying.

4.5.3 Landscape Factor Analysis

Landscape Factor 1 – Economic Growth

Colombia has experienced an average Gross Domestic Product (GDP) growth of 3.6% between 1998 and 2014 (The World Bank 2016c). Energy demand and economic growth have been traditionally correlated in Colombia with reduced energy demand during economic downturns, such as during the economic recession of 1999 and the economic deceleration of 2009; and increasing energy demand during economic upturns (Macías Parra 2013). The most reiterated aspect of how economic growth influences the adoption of wind energy is the augmented demand for electricity that is generated by the growth. As put by a representative of EMGESA, “economic growth has led to increased demand for energy that must be met by a more diversified energy mix, thus leaving the country’s dependence on hydro, and instead investing in new technologies such as wind energy, which is one of the most developed renewable energies today in the world”. As mentioned earlier, the increasing energy demand has been so far met mostly by thermoelectric. The new RE law will be crucial for insuring that the increased public and private capital that economic growth (LF1) generates positively contributes to wind energy development.

Representatives from EGCs also emphasized the combination of economic growth and climate change (LF3) as a driver for change towards alternative sources of energy. The increased demand for energy as a result of increased economic growth, together with increased concern for intensified climate related events, such as El Niño, is increasingly making wind energy a viable alternative. Research institutes also report an increase in research funding (F6a) for wind energy as a consequence of economic growth. An interesting remark from both research institutes and government officials is that since much of the economic growth is derived by exploitation of natural endowments such as oil and coal, a realization of finite nature of these resources could contribute to political decisions to preserve them, by investing in more alternative energies. Thus, paradoxically an economic growth based on fossil fuels could create the opportunity to better manage natural resources in the country.

Landscape Factor 2: Environmental Awareness

Environmental awareness is currently considered by the experts to have a small effect on TIS functions and the transition towards wind energy. At the same time, several study participants described it as an important factor for RETs diffusion and the overall sustainability of Colombia's future. Study participants expressed that there is a general lack of knowledge concerning environmental issues among citizens, which is largely explained by low level of education. As a representative of one of the research institutes put it, "it should start with our children, through early childhood education to make environmental awareness part of every child". Over the last decade, however, Colombia has experienced an overall rise in awareness for environmental issues. Climate change is now present in the minds of Colombians, in part due to the harsh consequences of El Niño/La Niña events the country has experienced. As a result, there has been an increase in the awareness concerning the role of wind energy and other RETs to combat global climate change. However, the perception of the government and EGCs, in particular, of the energy system in Colombia is that since it is a hydro-dominated system, it is already basically carbon neutral. While Colombia's energy system is relatively 'clean' as compared to many other countries, as previously mentioned the existing hydro-dependent energy system has been forced to increase investments in thermoelectric generation, in order to offset the risks from climate variability, which decreases the reliability and availability of hydro-power, especially during El Niño drought periods. Increased awareness amongst key actors in Colombia concerning the impacts of climate change on hydropower and the local and global environmental impacts from increased GHG emissions could facilitate the transition towards wind energy and other RETs.

Landscape Factor 3: Climate Change

Climate change was shown to have a large influence in Colombia and makes its presence in policy discussions. Climate variability impacts the heavily dominant hydro sector dependent on a steady flow of water. Going forward, the two real alternatives for Colombia are to either increase thermoelectric generation, which adds to greenhouse gas emissions, or to diversify its energy mix with wind and other RETs. The vulnerability to climate change is “an aspect that puts certain pressure for change in Colombia” (Representative of UPME).

“The pressure that climate change is putting on the decisions for renewable energy is fundamental” and “it forces Colombia to stop and reflect on its resources and what steps to take, and ultimately consider other forms of energy such as wind power” (Representative from DNP – National Planning Department). To illustrate, climate change concerns have resulted in a concrete implication, a strategy to reduce GHG emissions through the ‘Low Carbon Development Strategy’. In addition, several interviewees described the concern of climate change as a central factor in passing the 2014 RE law.

Furthermore, the decisions of EGCs are influenced by climate change not only by reducing the reliability of hydropower generation, but also affected energy prices. The price of energy is also influenced by climate variability, which creates insecurity for businesses. EGCs are forced to mitigate the risks posed by climate change by diversifying their portfolio. This insecurity has increased lobbying activities (F7a) by influential EGCs to expand resource mobilization (F6) for wind energy and other RETs.

Landscape Factor 4: Armed Conflicts

While the situation of the armed conflict has significantly improved in Colombia⁶⁹ over the last decades, armed groups and criminal gangs are still present and controlling the drug trade. The share of government expenditure for the military amounts to an average 12.1% over the last 15 years (2000-2014), more than twice that of most South American countries and even higher than the United States (SIPRI 2015).

⁶⁹ A peace agreement was signed between the Colombian Government and the largest guerilla group, FARC (Fuerzas Armadas Revolucionarias de Colombia) in 2016. Demobilization and disarmament of guerrilla combatants started early in 2017. Peace talks started in February 2017 with the second largest guerrilla group, ELN (Ejército de Liberación Nacional) in Ecuador.

Study participants confirmed a negative influence on investments and entrepreneurial activities by the persisting armed conflict in Colombia. From a business perspective, the primary consequence of the persisting armed conflict is higher interest rates for investments in Colombia. In the region with the highest wind capacity, La Guajira, the presence of armed groups has implied higher risks for new investor, leading to higher interests rates from financial institutions. Along with higher interest rates, a new technology such as wind power, which takes time to construct, is especially vulnerable to these insecurities, and implies higher project costs for assuring the security of personnel.

A noteworthy finding concerning the influence of armed conflicts on wind energy in Colombia is that was found to have a dual effect, namely positive and negative. Beyond the negative influence on large-scale wind projects discussed above, the armed conflict fueled innovations of smaller size (i.e., not large wind turbines suitable for wind parks) for wind energy and solar PV. More specifically, the conflict motivated the need for portable RETs solutions for soldiers that are stationed in remote areas of Colombia for longer durations. Consequently, the government directed military funding for the innovation of suitable RETs solutions. Thus, as a consequence of the armed conflict, innovative portable wind turbines and solar panels that could charge cell-phone or be used for other electronic devises are being developed at universities in Colombia.

To counteract the negative influence for large-scale wind projects, an interesting observation was made by university research groups who have been in contact with armed groups during wind energy studies. The claim that as long as a consultation is made with the local community and that they can prove that they are there for sole educational purposes, i.e. no political interest, the armed groups are less inclined to oppose their presence. Based on this observation, a community-based project that is successful in formulating and communicating the social benefits of the project may be able to reduce the risks imposed by armed groups.

Landscape Factor 5: Corruption

Reliable data concerning the level of corruption and its impacts on societies and entrepreneurial activities is difficult to obtain due to its informal and taboo nature. However, one study has estimated that between 1989 and 1999 corruption in Colombia was responsible for an annual loss of 1% of GDP, which in monetary terms equals approximately US\$ 750-800 million (Gallón Gómez and Gómez Portilla 2000). Despite several efforts from the Colombian government to curb

corruption, the country went from 57th to 94th place in the Corruption Perception Index ranking⁷⁰ between 2002-2012 (Gutierrez 2013).

Interviewees considered that corruption is not a significant issue at the central government level, but rather a problem once the resources have been allocated to local/regional governments. The perspective of several EGCs representatives is that corruption within the energy sector is not widespread, and has been much reduced as a consequence of the 1993/94 privatization of the energy sector. They, however, reiterated the concern of corruption in government, and recognize it as factor that influences society at large.

From the EGCs, there are no mentioned cases of dry-out of funds due to corruption, leading to the cancellation of an ongoing project. However, there is a clear consensus among experts that corruption has blocked the initiation of wind energy projects. Numerous interviewees expressed concerned regarding politicians requiring an informal payment in order to approve a permit for a project, or in other ways facilitate the initiation of a project. The informal payments contribute to making projects more expensive, which can result in the projects becoming financially unfeasible. Also, it is worth highlighting that some of the interviewees noted that they had been unwilling to pay the bribes and had opted for canceling projects in areas where bribes were required. Thus, corruption is deemed a very important landscape factor since even with the right economic and regulatory incentives in place, the expropriation of funds allocated for wind farms or the expectance of informal payments could reduce the positive progress made.

Landscape Factor 6: Inequality: Unequal Access to Quality Education

Unequal access to quality education in Colombia is manifested in two distinct ways. The first aspect is the difference in quality education between urban and rural areas, where the urban counterpart significantly outmatches rural areas. There are also discrepancies in quality between urban schools, but the contrast is particularly stark between urban and rural areas. Secondly, private schools are generally of higher quality than public schools. This is particularly true for primary and secondary levels, as Colombia has several high quality public institutes at the tertiary level. Unequal access to quality education at primary and secondary level perpetuates existing inequalities, whereas a graduate from an urban private school will have much greater opportunity to pursue higher education. As a result, many young people in Colombia are blocked from entering higher-level studies, either by unaffordable tuition fees or inability to qualify for universities enrollment due to poor quality at the primary and secondary level (The World Bank 2008).

⁷⁰ 175 countries participated in the 2012 study. A higher number in the ranking implies higher corruption in the country.

Existing discrepancies in education quality potentially influence the wind energy sector from through lower awareness of population in regard to environmental issues and the role of RETs, as well as a mismatch of personnel, or lack of sufficient qualified personnel, required to plan, design and maintain future wind parks. Experts in the government and research institutes stress that part of this mismatch can be attributed to the limited amount of eligible people for tertiary education. Another reason is the limited availability of specialized programs for wind energy. As mentioned during the analysis of function 2, the base for engineers in Colombia is good, which is reiterated by experts in the EGCs. However, EGCs and government agencies raised the lack of specialized university programs for Wind Energy and other RETs as an area of concern that will create a mismatch for future wind energy projects and other RETs investments.

The effect of unequal access to quality education on specialized human capital is of particular concern in rural areas. Even with qualified engineers in urban areas, the low technical capacity in rural areas to operate and maintain the energy system risks delaying repairs and the system coming to a halt when issues occur. The lack of human capacity in rural areas is not only associated with the low quality basic education but also the limited access to technical education in these areas. To conclude, mismatch can be explained by a lack of specialized programs on wind energy available in Colombian universities, which is exacerbated by the lower amount of tertiary graduates caused by unequal access to quality education, which is especially of concern in rural areas. In turn, this mismatch could prove to become a deterrent for wind energy investments, especially in rural areas.

4.6 Summary of Findings and Policy Recommendations

This chapter has aimed to explain the slow diffusion of wind energy in Colombia by analyzing the underlying processes that make up the innovation system in the form of functions, along with the influence of the wider context, in the form of landscape factors operating outside the focal wind energy sector. This section provides a summary of the findings explaining the slow diffusion of wind energy in Colombia, the influence of the selected landscape factors, along with policy suggestions for how to remedy existing barriers.

4.6.1 Landscape Factor Influence on Functions of the Wind Energy Sector

The study found several insights regarding the pressure that the landscape factors place directly on the TIS functions but also indirectly by influencing the existing regime. Figure 4.4 summarizes these findings, while indicating the relative strength of the influence of the different landscape factors on the TIS. Climate change proved to have a strong positive influence on several functions. For example, climate change was described to have been fundamental in the formation of the new RE law and the ‘Low Carbon Development Strategy’ (which falls under the

guidance of the search function), as well as having positive effect on legitimizing wind energy and contributing to an increase in government resource mobilization towards research on wind energy and other RETs.

Climate change also proved to indirectly influence functions by first putting pressure on the existing socio-technical regime, which in turn influences the wind energy sector. For example, climate variability and change and the accompanying unreliability of water availability has contributed to a realization amongst the largest hydro generating companies regarding the risk of not diversifying their energy portfolio. Moreover, wind energy was expressed as the primary alternative amongst RETs. As a consequence, formal lobbying (F7a) has been taking place by existing hydro companies to improve the conditions for wind energy diffusion has been taking place in the past couple of years.

Figure 4.4 Landscape Factor Influence on TIS Functions

Source: Author, based on analysis of interview data.
 Note: (+++/- - -) signifies strongest positive/negative influence, (++/- -) medium influence and (+/-) least influence.

The environmental awareness landscape factor was not considered to put significant influence on the creation of legitimacy for wind energy, and the contribution of environmental awareness on knowledge diffusion proved absent all together. The weak influence of environmental awareness can largely be explained by a widespread belief that the Colombian energy system is already clean, due to the large generation from hydro. While this is partly true in the short-term, measured only by greenhouse gas emissions, a misconception exists, both in the general public and amongst government officials concerning the medium and long-

term perspectives of hydropower. Building new hydro projects is becoming increasingly difficult due to the environmental and human effects of new dams. As a consequence, thermoelectric generation is increasing in order to cover an increasing demand for electricity and to mitigate the risks associated with more frequent and extreme 'El Niño' events. Thus, the energy mix in Colombia has shown an increasingly dirtier trend (i.e., higher greenhouse gas emissions) and environmental awareness in the country is not attuned to these existing realities. Therefore, additional knowledge diffusion (F3) amongst all actors concerning Colombia's current and future greenhouse gas emissions and the role of RETs is needed. The need for including topics of environmental awareness, including alternative energy generation in early childhood education was reiterated by experts as not only essential for increasing legitimacy for wind and other RETs but also for changing behavior in the Colombian population that would allow for consideration of sustainability concerns beyond energy supply (e.g., curbing energy demand).

Corruption was described as a strong blocking mechanism for entrepreneurial activities and government resource mobilization, with inefficiencies at the regional and local government level being emphasized as the main area of concern, while corruption in the central government and energy sector was described as less of an issue. The armed conflict in Colombia has contributed to elevated costs, in terms of higher interests rates and extra security to assure the safety of personnel, which has deterred entrepreneurial activities. However, the EGCs did not express a great concern over the impact of the armed conflict for future wind energy, and by drafting an inclusive community based project plan, this risk could be further reduced. A landscape factor that was not part of the initial framework but relates to the inclusiveness of new projects, involves the indigenous population in Colombia. Experts from EGCs expressed the approval of new projects to be significantly slowed down due to negotiations with indigenous populations. Clearer guidelines from the central government that would speed up the process from planning to implementation, while taking into consideration the demands and rights of indigenous populations and their culture, would facilitate the emergence of future wind energy projects.

Finally, the study also analyzed the influence that landscape factors exercise on each other (either positively or negatively) (see Fig. 4.5). For example, climate change related events, such as intensified El Niño, were found to positively affect environmental awareness. Corruption proved to have a negative effect on access to quality education. This reinforcing landscape-landscape interaction is of importance in the medium to long-term as it may strengthen other landscape factors that in turn could influence TIS functions in a positive (or negative) direction.

Figure 4.5 Landscape - Landscape Factor Influence

Source: Author, based on analysis of interview data.

Note: The (-) and (+) reflect negative and positive influence found in the study. Relative strength of influence between landscape factors is beyond this study.

4.6.2 Barriers to wind energy adoption – Functions weaknesses and policy suggestions

For the last 6 years, interest in wind energy amongst energy companies in Colombia, especially the hydroelectric generating companies, has risen. Entrepreneurial activities, in the form of planned projects and activities from incumbent actors for wind energy was found to be one of the strongest functions in the innovation system. However, despite the increased entrepreneurial activities for wind energy, several functions are acting as barriers for further progress and help explain the slow diffusion of wind parks in Colombia. Based on the data from the interviews and history event analysis, Table 4.3 provides a description of the specific barriers within each function, along with policy strategies that could reduce existing barriers and induce diffusion of wind energy in Colombia. The final compilation of the findings presented in Table 4.3 stresses the importance of a comprehensive approach to analyzing slow diffusion of a new technology. A diffusion of wind energy in Colombia will be best achieved by addressing weaknesses across the technological innovation system, while taking into account the barriers and drivers acting beyond the integral actors and activities (focal innovation system), as was done in the landscape analysis in this chapter.

The policy suggestions displayed in Table 4.3 are restricted to policies that could be implemented in the short or medium term. More structural barriers were also revealed in the analysis. These structural barriers are more complicated to implement and can in most cases only be addressed in the long-term. An example of this was the rigidity and low institutional and organizational capacity in Colombia, which would require significant and lengthy institutional and organizational reforms. Another structural barrier that was raised by the experts was the need to redesign the curriculum in Colombian schools to introduce environmental sustainability and the role of RETs from an early age. This too

would require longer time to implement, although less complicated than institutional and organizational reforms.

Despite the existing barriers to wind energy diffusion in Colombia, there is cause for optimism. The study has identified positive trends across a majority of functions. The new RE law places a focus on renewable energy technologies that if aptly nurtured could result in improved conditions for several functions, e.g., through a special fund to channel international financing, additional targets, and subsidies for wind energy. The increased activities in universities over the past years, in terms of research groups specialized in wind and other RETs, are also contributing to reducing the existing knowledge gap, and are likely to result in more discussions and diffusion of knowledge. The existence of high quality universities, wide availability of engineers and the positive trend of increased research focus on wind energy technologies, provide a good base for a stronger knowledge development function. R&D on RETs has already resulted in small-size innovations for wind and solar energy. For large turbines, however, Colombia will have to, for the time being, continue to rely on purchasing the technology from abroad.

Table 4.3 Summary of Findings and Policy Suggestions

Functions	Barriers within Functions	Policy Suggestions
Adaptive Capacity	<ul style="list-style-type: none"> - Lack of programs in tertiary education with specialized focus on Wind and other RETs - Low to no human capacity in rural remote areas - Low institutional and organizational capacity 	<ul style="list-style-type: none"> - Increase number of Master and Doctoral programs with RETs focus - Vocational programs to develop technical skills for installation and maintenance (especially in remote rural areas) - Limit shorter term government contracts to retain knowledge
Knowledge Development	<ul style="list-style-type: none"> - Insufficient knowledge base and political support for developing large turbines or improving wind technology in Colombia 	<ul style="list-style-type: none"> - Additional financial support to expand ongoing research collaboration and knowledge development for wind in universities - Develop medium and long-term plan of government support for facilitating knowledge development for wind energy
Knowledge Diffusion	<ul style="list-style-type: none"> - Insufficient dissemination, especially between wind energy experts of research institutes, government and industry 	<ul style="list-style-type: none"> - A more active mediating government role in reducing knowledge discrepancies among actors (e.g., arranging yearly government sponsored conferences)
Guidance of the Search	<ul style="list-style-type: none"> - Lack of clear targets (dates and percentages of wind energy generation) - Decision making hampered by bureaucracy and institutional rigidity 	<ul style="list-style-type: none"> - Build on the new RE law and set clear short to long-term targets and specific subsidies for import of material for wind generation

Market Formation	<ul style="list-style-type: none"> - Low KWh price from hydro combined with lack of pricing policies for wind - Lack of targeted subsidies in place for import of wind energy material (turbines, etc.) 	<ul style="list-style-type: none"> - Introduce pricing policies (feed-in tariffs, etc.) - Provide specific tax benefits for wind - Incorporate social and environmental costs in energy price generated by large hydro and thermo-electrics
Resource Mobilization (Government)	<ul style="list-style-type: none"> - Insufficient resources for R&D - Insufficient resources to extend grid in non-interconnected areas 	<ul style="list-style-type: none"> - Additional resources for research groups at universities, and to improve collaboration between government, EGCs and universities - Targeted funds to map cost-benefit for wind and its complementary qualities to existing hydro generation (as requested by EGCs.) - Increased funding for extending national grid (SIN)
Resource Mobilization (International loans and grants)	<ul style="list-style-type: none"> - Availability (from the lender side) of funding is <u>not</u> considered a barrier - Skepticism of international loans for wind - Low government interest and lack of specific entity to effectively disburse funds for WE projects 	<ul style="list-style-type: none"> - Following through on mentioned plans to create a specific fund for international financing and assign sufficient qualified personnel to oversee an effective distribution of funds towards wind energy projects
Creation of Legitimacy (formal lobbying)	<ul style="list-style-type: none"> - Formal lobbying for wind is dominated by a few large hydro companies with risk of slow action - Thermoelectric companies pose opposition to wind energy 	<ul style="list-style-type: none"> - Government sponsored workshops and conferences aimed at reducing knowledge gap among influential actors (government departments, incumbent actors and experts researchers) regarding the cost-benefit of wind energy
Creation of Legitimacy (informal lobbying)	<ul style="list-style-type: none"> - Insufficient and scattered informal lobbying - Limited public engagement and support 	<ul style="list-style-type: none"> - Workshops and information campaigns geared towards the general public - Develop a forum where environmental groups, research groups and public voices can be unified and heard
Entrepreneurial Activities	<ul style="list-style-type: none"> - Knowledge gap among actors concerning potential of wind - Insufficient infrastructure i.e. energy grids connecting areas with high wind potential - Lack of pricing policies and targeted subsidies 	<ul style="list-style-type: none"> - Improvements across several functions will help remove barriers for this function. A special emphasis on knowledge diffusion (e.g., more conferences with private and public sector involvement); Guidance of the search (clear targets for wind); and Market Formation (e.g., tax exemption for wind, feed-in tariffs).

4.7 Concluding Remarks

In this chapter, a multitude of barriers that are obstructing the takeoff of wind energy projects in Colombia have been identified and analyzed by utilizing a comprehensive framework of system functions and landscape factors. By including landscape factors to complement the TIS function analysis in Colombia, the analysis took into consideration ‘pushes and pulls’ from the wider context on the diffusion of new technologies in a developing country context. The results of this extended TIS function approach, and the indicated influence from the landscape factors suggests that delimiting the system by the integral actors and activities (focal system) alone is insufficient, and that the landscape factors should instead be treated as endogenous to the system. Using an extended TIS function approach in future studies in developing countries can help shed light on additional barriers and drivers to RETs adoption, and widen the alternatives of both short and long-term policies to address them.

That said, while this chapter has confirmed the value of including the landscape analysis to complement the TIS function approach in the case of Colombia, certain flexibility is to be preferred when selecting landscape factors for future studies. For example, the study revealed the influence of indigenous communities on the implementation of wind energy projects in their territories, which was not included in the original list of landscape factors. Additional case studies that combine the TIS function analysis with the wider context in developing countries are needed to further develop the extended TIS function approach utilized in this chapter.

Chapter 5. The Impact of Environmental Education on Environmental and Renewable Energy Technology Awareness: Empirical Evidence from Colombia^{71,72}

5.1 Introduction

Already in 1998, the Human Development Report stressed the significant pressure on the environment that was being generated by human consumption (UNDP). Since then, human consumption of natural resources has steadily increased and according to the ‘Planetary Boundary’ framework, four out of nine Earth system processes have passed the sustainable boundaries (Steffen et al. 2015).⁷³

Energy efficient and cleaner technologies are considered an essential aspect in reducing the human impact on the environment, while assuring a high quality of life (Dell and Rand 2001). The pressing concern of climate change has placed an increased focus on Renewable Energy Technologies (RETs) (IPCC 2012). In the other chapters, environmental awareness and specific awareness for RETs have, in the context of technical innovation systems, been highlighted as a framework condition/landscape factor that may positively influence technological transitions towards RETs. Therefore, improving the understanding of how a positive framework condition can be strengthened is an important avenue of research.

From a wider sustainability perspective, learning how to augment environmental awareness is also of importance, as relying solely on technological solutions to meet the challenges of sustainability will likely not be effective. Parallel to technological advances, human attitudes and behavior towards energy use and overall consumption ought to be addressed for sustainability goals to be viable. Without simultaneously tackling an augmented human consumption, much of the

⁷¹ An earlier version of this chapter has been submitted to a peer-reviewed journal (currently under review). This chapter has been co-written by Hans-Erik Edsand and Tobias Broich (UNU-MERIT/Maastricht Graduate School of Governance, University of Maastricht). Data collection, selection of variables, preparation of data and analysis of the results was a joint effort. Hans-Erik Edsand was the lead author with the main responsible for designing the study and carrying out the literature review. Tobias Broich ran the econometric modeling in Stata and performed initial interpretation of results.

⁷² The authors are very thankful to Professor Dr. Pierre Mohnen (UNU-MERIT) for his contributions to this chapter.

⁷³ For more information concerning the Planetary Boundary framework see (Rockström et al. 2009).

advancements and efficiency gained by new technologies risk being lost, as emphasized by the rebound effect.⁷⁴ Thus, devising strategies to more effectively generate environmental awareness and awareness for RETs specifically should be considered an essential aspect of sustainability efforts and support for policy development.

Over the past few decades, the international governmental and non-governmental organizations, policymakers, and education ministers have continually argued to enhance the environmental literacy of their citizens. Environmental education (EE) is considered one of the silver bullets in developing environmental knowledge, awareness and attitudes at the student age already in order to encourage civic participation for sustainable development (Hungerford and Volk 1990). Whether environmental education can be considered a major determinant of improved environmental literacy is however not yet clear. A vast amount of literature has examined the impact of several individual-related and school-related factors on environmental literacy, mainly in developed countries (Hungerford and Volk 1990; Iozzi 1989; Kollmuss and Agyeman 2002; OECD 2007). The literature that looks at the relationship between environmental literacy and schools as well as individual characteristics in the developing world is surprisingly rare. Understanding how certain student- and school-related factors can (or cannot) influence environmental literacy, both in the developed and developing world, “can help to further improve educational policies, programs, and practices for sustainable development” (Lin and Shi 2014, 74).

Since previous research on the student- and school-level determinants of environmental literacy is (i) surprisingly sparse, (ii) mainly focused on developed countries, and (iii) is mostly of qualitative and philosophical nature, this study uses quantitative estimation techniques to assess several student- and school-level determinants of environmental literacy for a developing country, namely Colombia. The decentralized education system in Colombia, combined with discrepancies in both quality and dedication to environmental education between schools provides for an interesting developing country case study. By using Colombian PISA (Programme for International Student Assessment) 2006 data on environmental awareness and other environmental output measures, our study addresses the following main research questions:

1. To what extent can environmental education (EE) at school explain variation in environmental awareness of 15-year olds?
2. To what extent can environmental education (EE) at school explain variation in awareness for RETs of 15-year olds?

⁷⁴ See Chapter 1 for additional discussion about the rebound effect.

Besides the two main research questions, this chapter also addresses two sub-research questions:

3. Do other individual-level characteristics matter? That is, do personal, demographic characteristics, student science abilities, or parental values and characteristics have a differential effect on varying levels of environmental awareness and awareness for RETs?
4. Do specific school characteristics matter? That is, to what extent does the school ‘infrastructure’ (public versus private, school size, teacher-student ratio, teacher shortage, proportion of qualified/certified teachers, quality of educational resources, etc.) promote environmental awareness and awareness for RETs?

We use a multilevel mixed-effects linear regression model, where the individual observations are nested within schools. Based on the maximum likelihood estimation method, we estimate a linear mixed model which contains both fixed effects and random effects. Our empirical results only provide weak evidence that environmental education can promote a higher level of environmental awareness. The relationship between environmental education and awareness of RETs is even weaker. Our findings therefore suggest that environmental education should not be considered a silver bullet in promoting environmental literacy among students. Additionally, we find more reliable predictors for environmental awareness than for awareness of RETs. Overall, the socio-economic status, stronger student science abilities, parent characteristics and a few school-level characteristics such as quality of education resources and school ownership (public versus private) seem to be decisive factors for varying levels of environmental literacy among students in Colombia.

This chapter fits into the literature that explores individual and school-related determinants of environmental literacy (Coertjens et al. 2010; Lin and Shi 2014). Coertjens et al. (2010) empirically test whether schools can make a difference in promoting environmental awareness and attitudes among students using cross-sectional data of the OECD PISA 2006 for the Flemish part of Belgium. (Lin and Shi 2014) investigate the relationship between individual and school-related factors and environmental literacy for the US and Canada using OECD PISA 2006 data. Compared to the two aforementioned studies, our analysis differs in four major ways. First, our study addresses a much more specific research question compared to the studies by Coertjens et al. (2010) and Lin and Shi (2014). Second, the focus of this chapter is on a developing country, rather than a developed country. Third, we introduce a novel dependent variable as proxy for environmental literacy, namely the level of awareness for renewable technologies. Fourth, we use potential confounding factors at the school level as control variables that have not been used in previous studies.

The rest of the chapter is structured as follows. First the existing literature on environmental awareness and environmental education is briefly summarized. The

following section provides country information on Colombia, followed by a description of the data used in this chapter. Next, the methodology is described and the empirical findings presented. The last section concludes.

5.2 Environmental Awareness

Environmental awareness has been defined as “the ability to emotionally understand the surrounding world, including the laws of the natural environment, sensitivity to all the changes occurring in the environment, understanding of cause-and-effect relationships between the quality of the environment and human behaviour” (UNEP 2016, chap. 4.2). This awareness for the environment has been identified as a facilitating factor for achieving overall pro-environmental behavior⁷⁵ in human societies (Vlek and Steg 2007).

5.2.1 Environmental Awareness and Renewable Energy Technologies

Environmental awareness in the broader sense has been raised as a facilitating factor to move societies towards a more sustainable energy mix. An increased environmental awareness has been described as putting pressure on incumbent energy providers to diversify its energy supply, which provides opportunity for new technologies, such as RETs, to enter the market (Smith, Voß, and Grin 2010). On the demand side, higher environmental awareness has been shown to increase the preference for consuming energy from RETs (De Groot et al. 2012; Van der Werff, Steg, and Keizer 2013). Moreover, the driving influence on policy makers and environmental regulations by an environmentally aware public has been well documented (Guha 1999).⁷⁶

Reversibly, a lack of awareness for RETs can act as a barrier, in the form of lowered social acceptance for new technologies (Wüstenhagen, Wolsink, and Bürer 2007). In developing countries, the lack of environmental awareness and awareness for the costs and benefits of RETs has been found to have a significant negative influence on RETs adoption (Kennedy and Basu 2013; Luthra et al. 2015).

⁷⁵ Note that the data used for this chapter allows for analyzing the link between environmental education and awareness (attitudes), which can provide insights for future studies of changed behavior (actions taken). Analyzing changed behavior requires additional data collection over time, and therefore beyond the scope of this chapter.

⁷⁶ See also the work by Stern et al. (1999) and P. C. Stern (2000) on the value-belief-norm theory, which discusses social movements and environmentalism.

5.2.2 Explaining Different Levels of Environmental Awareness

Three Broad Competing Hypotheses

Inglehart's (1997; 1977; 1990) post-materialism hypothesis argues that as societies advance economically they tend to pursue more post-materialistic goals such as self-expression, political freedom, environmental protection and quality of life more general. Put differently, the post-materialism hypothesis claims that a certain level of material standard must be achieved before other aspects such as environmental concern can be given focus. Seminal contributions by Dunlap et al. (1993; 1995; 1997) challenge Inglehart's post-materialism hypothesis arguing that environmental concern must be considered a global phenomenon that is not restricted to a few wealthy countries, but also concern countries with lower per capita material status. Based on earlier work on the development of a new 'ecological paradigm' (R.E. Dunlap and Van Liere 1978), Dunlap and Mertig's (1995) empirical work suggests that environmental concern is in fact predominately negatively correlated with per capita GNP.⁷⁷

The third hypothesis is deeply rooted in classical economic theory (Baumol, Oates, and Blackman 1979; B. C. Field 1994). This approach stresses the importance of prosperity and economic affluence. It argues that the quality of environment should not only be regarded as a public good but also a private good: as the economic income of the population rises, the demand for a better quality of environment increases. This line of reasoning suggests a positive relationship between wealth and environmental concern. The quantitative evidence, however, remains ambiguous (Diekmann and Franzen 1999; Israel and Levinson 2004). While the study by Diekmann and Franzen (1999) suggests that the relationship between wealth and environmental quality is linear, Israel and Levinson (2004) argue that the relation is concave (i.e. the marginal willingness to pay for environmental quality increases at a decreasing rate and might eventually decline again).

Commonly Used Indicators to Explain Environmental Awareness

Much of the previous research that aimed to explain different levels of environmental awareness across individuals has focused on demographic factors. These demographic indicators include age and/or birth cohort (Dietz, Stern, and Guagnano 1998), personal values (Karp 1996; de Groot and Steg 2007), ethnicity (Howenstine 1993), religion (Biel and Nilsson 2005; Hand and Van Liere 1984), gender (Blocker and Eckberg 1997; Zelezny, Chua, and Aldrich 2000) and level of

⁷⁷ Note that GNP (Gross National Product) was used in these articles, rather than GDP (Gross Domestic Product) that is used in contemporary research.

education (Gelissen 2007). Age, and education level were found to be good predictors of environmental awareness, while gender and income have yielded mixed results (Ahern 2012).⁷⁸

Beyond the individual factors, the wider socio-economic context also helps explain people's level of environmental awareness (P. C. Stern 2000). Based on the mentioned sociological theory of post-materialism (Inglehart 1977; Inglehart 1990; Inglehart 1997), several studies have focused on the impact of a country's economic affluence – measured by GDP (GNP) per capita – on environmental awareness and attitudes (Brechtin 1999; Franzen 2003; Kidd and Lee 1997; Panayotou 1993; Panayotou 1997). The overwhelming majority of these studies suggests that stronger environmental awareness and attitudes are positively associated with a higher level of economic development.

Examples of other factors that have been identified as potential determinants for environmental awareness include the openness of the political system (Scruggs 2003; Zahran et al. 2007), political preferences (Fransson and Garling 1999), the level of democracy (Neumayer 2002), the length of the country's existence (Hershfield, Bang, and Weber 2014), economic inequality (Magnani 2000), rural versus urban living environment (Arcury and Christianson 1993; Berenguer, Corraliza, and Martin 2005), the degree of urbanization (Wilson 1984), population density (Brechtin and Kempton 1994), enrollment ration in tertiary education (Goetz, Debertin, and Pagoulatos 1998), happiness (Frey and Stutzer 2002; Welsch 2002), choice of environmentally-friendly technology (Acemoglu, Aghion, and Hémous 2014; Acemoglu et al. 2012; Bovenberg and Smulders 1995; Yakita 2009), forest conservation (Pawar and Rothkar 2015), environmental degradation (Givens and Jorgenson 2011) and cultural conditions (Oreg and Katz-Gerro 2006).

Another contextual factor that can influence environmental awareness are schools and specifically the type of information given at schools concerning the environment and sustainability. The influence of environmental education at schools as an indicator has not received as much attention in previous empirical studies. Given that the total instruction time in formal schooling alone can range between 4,500-8,500 hours between the ages of 7-14, schools have a unique position in influencing childrens' and adolescents' norms and values.⁷⁹

⁷⁸ Older birth cohorts (higher age) showed to have a lower environmental concern than newer (younger) cohorts. Higher education attainment was associated with a higher degree of environmental concern. People with conservative political preferences were associated with a lower concern for the environment (Ahern 2012).

⁷⁹ Data example is based on OECD countries (Poland: Low-end; Italy: High-end) from OECD's Education at a Glance (2011).

5.2.3 The Concept of Environmental Education

Broadly speaking, environmental knowledge includes both knowledge *of* and knowledge *about* the environment (Lucas 1979). According to the OECD (2007), knowledge *of* can be defined as the student's ability to recall and understand a range of various environmental concepts, problems, and issues. Knowledge *about* can be described as the means (scientific inquiry) and goals (scientific explanations) of environmental education.

The concept of environmental education is not new; it has been discussed for several decades. While no universally accepted definition of environmental education exists, the objectives and categories set out by United Nations Educational, Scientific and Cultural Organization (UNESCO) in the late 1970s are commonly referred to in the literature (Marcinkowski 2003). The 1978 final report of the Tbilisi conference describe the role of environmental education as to “enable individuals of all ages and from all backgrounds, to assimilate the values, the basic concepts and the practical knowledge which will help them to an awareness of environmental problems, help them to adapt their everyday behaviour accordingly and thus make a useful contribution to the joint effort to safeguard the environment” (UNESCO 1978, 67).

The ultimate objective of environmental education is to promote environmental literacy among citizens. Environmental education “resonates with the model which refers to the environment in a holistic, human-oriented approach as interacting biophysical (organisms and life-support systems), social (people living together), economic (livelihood, money and services) and political (power, policy and decisions) dimensions” (Goldman, Assaraf, and Shaharabani 2013, 517). Environmental education also fits well into the socio-ecological system (SES) framework (Ostrom 2009).

In addition to environmental education, various forms of information dissemination can contribute towards raising environmental awareness. Information concerning the environmental impact from human material and energy consumption can and should be addressed on several fronts simultaneously. Government channels of communication, campaigns by environmental organization and the media are examples of other possible conduits for information dissemination (Dincer 2000).

However, there are good reasons to focus on the role of environmental education in basic education.⁸⁰ First, adolescence constitutes the period when moral awareness, individual philosophies, and belief systems are being formed (Damon and Hart 1988).⁸¹ Second, there is evidence that suggest that the absorption of new knowledge (fluid intelligence) and concepts is very high at this age (Savage et al. 1973). These findings do not imply that education and awareness building should not also be directed towards adults, but rather to emphasis the opportunity of introducing new concepts such as environmental sustainability during adolescence. Finally, the need to re-connect children with nature has been emphasized in previous research, referring to an existing ‘nature-deficit disorder’ (Louv 2008). Schools can serve as an important source of information regarding environmental sustainability and amend existing disconnects with nature.

Role of School Education in Generating Environmental Literacy

Literature that examines the impact of school education on environmental literacy is surprisingly sparse. Previous empirical studies on the effects of schools and environmental education are limited and are largely restricted to developed countries. Bradley, Waliczek and Zajicek (1999) investigate the relationship between environmental knowledge and environmental attitudes of US high school students in Texas. Their study suggests that students with higher knowledge scores have more favorable environmental attitudes compared to students with lower knowledge scores. In contrast, DeChano (2006) does not find a significant relationship between environmental knowledge and environmental attitude using data from high school students in Chile, England, Switzerland and the United States.

Negev et al. (2008) study the effects of environmental education in Israel. The authors do not find a significant correlation between environmental knowledge and environmental behavior. Another contribution that uses Israel as a case study examines the impact of environmental education programs conducted by out-of-school environmental organizations: while the program increased student’s sensitivity to human–environment interrelationships, its impact on the cognitive domain, in developing a more systemic understanding of environmental issues, was limited (Goldman, Assaraf, and Shaharabani 2013).

⁸⁰ Based on International Standard Classification of Education (ISCED) basic education encompasses primary and lower secondary education (UNESCO-UIS 2012).

⁸¹ This further motivates the use of PISA statistics to analyze environmental awareness, which evaluates 15 years olds, who are in the adolescence range (12-18 years).

A study by Coertjens et al. (2010) provides interesting insights into the role of schools, but is limited to a region within Belgium (Flanders). While several student-related factors like gender, immigrant status and socio-economic status seem to explain differences in student's environmental attitudes and awareness, the authors also show that school policies matter: "schools in which science is taught in a more hands-on manner are associated with higher student environmental awareness whilst environmental learning activities are associated with more pro-environmental attitudes amongst students" (Coertjens et al. 2010, 497). A similar contribution by Lin and Shi (2014) examines individual and school-related determinants for environmental literacy in North America (Canada and USA). The authors find that, in general, increased environmental knowledge is associated with a deeper sense of responsibility toward positive environmental impact. However, the study also provides 'only' mixed results with regard to individual-level factors for both countries related to environmental awareness, attitudes, and behavior.

There exist only a few studies that empirically test the relationship between environmental education and environmental literacy in developing countries. Using Cote d'Ivoire as a case study, Borchers et al. (2014) found that extra-curricular environmental teaching in primary schools has a strongly positive effect on environmental knowledge and attitudes towards the environment. Haryono et al. (2014) find a significant impact of environmental education in school on students' knowledge but not on students' environmental attitudes and awareness in the Indonesian city of Probolinggo. A case study on rural Madagascar shows that children in villages who received environmental education had higher environmental knowledge and more positive environmental attitudes than children in the villages not exposed to the environmental education (Rakotomamonjy et al. 2015).

In this chapter, we aim to strengthen the overall empirical knowledge base concerning the effect of environmental education in generating environmental awareness and awareness for RETs. Moreover, we will address an existing research gap by gaining a deeper understanding of the relationship between environmental education and environmental literacy in a developing country context, namely Colombia.

5.3 Country Background – Colombia

5.3.1 Economy of Colombia

Colombia is a highly diverse middle-income⁸² developing country, both in terms of ecology and population. Its population of almost 50 million people consists of a mixture of people with indigenous, Spanish, European, African and Middle-Eastern descent. Since the 1999 recession, Colombia has experienced a stable and high economic growth, with an average annual GDP growth of 4.4 percent between 2000 and 2014 (The World Bank 2016c). Despite a positive economic development in the past decades, inequality in Colombia persists, with a Gini coefficient for income distribution of 0.55 in 2011, roughly the same as in 2003 (Moller 2012). The Gini coefficient ranges from 0 (perfect equality) to 1 (perfect inequality) and generally countries range between 0.3-0.5 (Haughton and Khandker 2009).

The strong economic performance has led to sharp increases in demand for energy as well as material and natural resource consumption. The increase in energy demand has primarily been covered by a rapid expansion of thermo-electric energy generation, rather than diversifying its energy mix towards RETs (MRI, UNC, and NUMARK 2010). Raising environmental awareness and awareness concerning the costs and benefits from RETs in the Colombian society serves as one important aspect in moving the country towards a sustainable development path. In this chapter, we focus on one of the strategies for raising awareness in Colombia; namely through the education system.

5.3.2 Education System in Colombia

The constitution of 1991 introduced compulsory school for children between 5-15 years of age. At the same time, the Colombian education system became largely decentralized giving autonomy and academic decision making to sub-national governments (Faguet and Sánchez 2014). The decentralization process of the education system in Colombia was part of a wider decentralization process that began in the late 1970s.⁸³ In contrast to other countries where decentralization was

⁸² Based on the World Bank income (GNI per capita of countries) classification (low, lower-middle income, upper-middle income (all considered as developing countries), and high income. In 2006, Colombia was classified a low-middle income country. According to the latest income classification (2015) Colombia was considered an upper-middle income (The World Bank 2016b).

⁸³ J.-P. and Sánchez (2014) provide an insightful account of Colombia's decentralization process and its impact on access to social services. Colombia's decentralization process

implemented rapidly, such as Bolivia (Faguet and Sánchez 2008), the Colombian process took around 25 years. In late 1991, the Colombian government established the Programa de Ampliación de Cobertura de la Educación Secundaria (PACES), or Program for Coverage Expansion in Secondary Education, as part of a wider decentralization effort and as an attempt to (i) expand private provision of public services (King et al. 1997), (ii) expand school capacity and (iii) to raise secondary school enrollment rates (King, Orazem, and Wohlgemuth 1999).

Several studies have examined the effects of Colombia's decentralization on education. According to a World Bank study, the decentralization process resulted in a significant increase in funding for public education in Colombia, from 3.3 percent of GDP in 1993 to 4.75% in 2007 (The World Bank 2008). As a result, access to primary as well as lower and higher secondary education has significantly improved.⁸⁴ Angrist, Bettinger, & Kremer, (2006) found that the PACES program increased secondary school completion rates by 15-20 percent and improved student test scores. Their study suggests that the PACES program and the decentralization process of the education system in general had a positive effect on Colombia's education performance. Other studies, however, show that this effect was not homogenous (Melo 2005; Sánchez 2006). Melo, (2005) highlights the disparities in performance (technical and allocation efficiency in the provision of public education) between the 32 departments in Colombia, even though all departments were under the same legislature.

Núñez et al. (2002) find a clear private school advantage: their empirical results suggest that the school sector plays a fundamental role in explaining existing gaps in student achievement and attainment in Colombia. While J.- Faguet and Sánchez (2008) find improved enrollment rates in public schools and a shift from infrastructure investment towards primary social services as a result of decentralizing education finance for the period 1994-2004; the result was mainly driven by the behavior of smaller, poorer, more rural municipalities. Their findings are based on a rich database that covers over 95 percent of Colombian municipalities.

Figure 5.1 portrays public, private and total school enrollment data for Colombia over the time period 1994-2004. School enrollment in 1994 is indexed to one. While public and private enrollment trends are similar in the mid-1990s, the slopes diverge from the early 2000s onwards, leading to a large gap between both

began in the late 1970s and initially only included fiscal measures aimed at strengthening municipal finances.

⁸⁴ The access to schooling was further guaranteed in 2012, by introducing free schooling until the end of upper secondary level (15-16 years of age/grades 10-11) (OECD and IBRC/The World Bank 2012).

education systems. Overall, the decentralization of Colombia’s education system led to a 20 percent increase in total school enrollment but the effect was unequally distributed: public school enrollment rose by 30 percent while private school enrollment dropped by 7 percent.

Figure 5.1 Public and Private School Enrollment in Colombia, 1994-2004

Source: J.- Faguet and Sánchez (2008).

A more recent study by Faguet and Sánchez (2014) suggests that the improved school enrollment rates in public schools due to decentralization were mainly driven by financial contributions of local governments. The authors conclude that “decentralization appears not to improve public schooling at the expense of private schools, but rather to promote the idea of education more generally” (Faguet and Sánchez 2014, 245). At the same time, however, the high inequality in the economy is also reflected in the education system. Wide discrepancies in the quality of education between different parts of the country still persist, especially between rural and urban areas (Rangel and Lleras 2010). Focusing on the Colombian city of Cartagena, Rangel and Lleras (2010, 291), find that even though family socio-economic background influences student achievement, “school [poverty] composition and school resources explain as much as half of the effects of family background on student achievement”.

There have been national efforts of introducing specific programs on environmental education with the aim of enabling students to become more responsible citizens (The World Bank 2008). However, the implementation of national educational directives is ultimately carried out by the autonomous schools at the local level, which results in differences between schools in their emphasis of environmental education. Overall, we find Colombia an appropriate case study for this chapter, due to its role as an emerging middle-income country with a need for environmental awareness to coincide with the increased demand for energy and

overall consumption. The decentralization of academic decisions in Colombia, combined with discrepancies in quality between schools, also provides for an interesting case study, due to varying levels of overall learning and dedication to environmental education between schools.

5.4 Data and Methodology

5.4.1 Sample

In this section, we will utilize the 2006 PISA dataset for Colombia to analyze the effect of environmental education on awareness. The 2006 PISA dataset provides a rich dataset for OECD and partner countries on the 15-year old students, parents and schools, including a specific survey on environmental education, awareness and attitudes (OECD 2007; OECD 2009). The selection of schools was made by PISA using random selection, making the sample representative for the Colombian school population (OECD 2007). The final sample for Colombia consist of 4478 Students in 165 schools.

Individual- and School-Level Variables

Certain variables were available on the individual (student or parent) level, while other variables were aggregated on the school level. In order to maximize the number of observations in our analysis, we decided to keep the data on the individual level by harmonizing the school level data with the individual level. This was achieved by assigning the school level data to students with the corresponding school identification number. For most of the variables we used the scales developed by PISA. A detailed description of the construction of theses scales is available in the PISA 2006 technical report (OECD 2009).⁸⁵ Each of the PISA scales are based on different questions, including multiple items and varying response alternatives for each question. The questions that the scales are based on are briefly discussed in the text. The complete questionnaires for the scales are available in Appendix II. The reliability for each scale, based on Cronbach's

⁸⁵ For this dataset PISA used scaling models that are based on the Item Response Theory (IRT) methodology, that helps determine the fit for the pooled sample. Unless otherwise noted, the items of the questionnaires were inverted for IRT scaling, so that a positive WLE (Weighted Likelihood Estimation) scores indicate a higher level of the respective scale. For example, a positive WLE score would indicate a higher *enjoyment for science* (one of the control variables included in this study) (OECD 2009).

alpha,⁸⁶ is shown in Table 5.1, together with the summary statistics for the variables included in our study.

Dependent Variable

In order to test our main research questions in this chapter, we chose two dependent variables. As proxy for environmental awareness amongst 15-year old students in Colombia, we selected the *Envaware* variable, constructed by PISA (OECD 2009). *Envaware* is a scale variable which is based on a questionnaire with five items. The questionnaire asks students about their awareness concerning (i) greenhouse gases, (ii) genetically modified organisms (GMO), (iii) acid rains, (iv) nuclear waste and (v) consequences of clearing forests for other land use. The answers were measured on a four-point Likert scale, with the answer categories ranging from, 'I have never heard of this' (1 point) to 'I am familiar with this and I would be able to explain this well' (4 points). The complete questionnaires for *Envaware* and all subsequent scales that are not fully described in the main text are available in Appendix II.

To address our second research question, we chose a single item from the PISA student questionnaire as proxy for RETs awareness. The single item asks how much students agree with the statement that 'Electricity should be produced from renewable sources as much as possible, even if this increases the cost'.⁸⁷ The answer categories included 'strongly disagree' (1 point); disagree (2 points); agree (3 points) and 'strongly agree' (4 point). We created the binary variable *Retaware* which is equal to one if the student either 'strongly agreed' or 'agreed' to that the question (0 otherwise).

In order to check whether our empirical results from our main explanatory variable varies depending on the measure of our main dependent variables (*Envaware* and *Retaware*), we decided to include three additional environmental output measures as dependent variables. The three additional dependent variables are: (i) responsibility for sustainable development (*Respdev*); (ii) environmental optimism (*Envopt*) and (iii) perception of environmental issues (*Envperc*) (OECD 2009). Similar to *Envaware*, those three variables are also scale variables. *Respdev* is made up by seven items pertaining to sustainable development; e.g., protection of endangered species, car emissions or waste management. *Envopt* and *Envperc* consist of six items concerning student's perception and optimism about aspects

⁸⁶ Cronbach's alpha is a statistic which is used as a measure of internal consistency or reliability (see Cronbach, 1951).

⁸⁷ This question is combined with six other questions to form another environmental output measure, namely responsibility for sustainable development (*Respdev*).

such as air pollution, energy shortages or nuclear waste (see Appendix II for a detailed description).

Main Explanatory Variable

Our main explanatory variable, environmental education (*Envedu*), is also a scale variable and is constructed based on a questionnaire about learning of environmental topics, denoted *Envlearn* by PISA (OECD 2007; OECD 2009). In the questionnaire, school principals are asked to what extent their respective school organizes activities aimed at learning about environmental topics. The scale consists of five items, namely (i) outdoor education, (ii) trips to museums, (iii) trips to science and/or technology centers, (iv) extracurricular environmental projects (including research) and (v) lectures and/or seminars (e.g. guest speakers). The principals were given the response alternatives ‘yes’ and ‘no’ to whether these activities occurred at their school (OECD 2009). Figure 5.2 plots environmental awareness against environmental education. The bivariate correlation between the two variables is 0.0868 and statistically significant at the 1 percent level.

Figure 5.2 Relationship between Environmental Education and Environmental Awareness in Colombia

Source: Authors’ own calculations based on OECD (OECD 2007; OECD 2009).

Student Level Control Variables

To account for potential bias we utilize an extensive list of carefully considered control variables at the student, parent and school level. The control variables on the individual student level include gender, immigration status, age and a socio-

economic index that captures the economic, social and cultural status (ESCS) of the student. The ESCS index is constructed by PISA (OECD 2009).⁸⁸

Previous literature has also emphasized the role of science in shaping environmental awareness and behavior. Littledyke (2008, 1) argues that “science education has an important part in developing understanding of concepts that underpin environmental issues, leading potentially to pro-environmental behaviour”. Thus, motivated by his and other previous findings, we also control for science ability at the student level. We include six PISA constructed scales: four forms of science teaching styles, enjoyment of science and science activities.

The first four science teaching indices capture student’s reports on the frequency of four different forms of teaching, i.e., ‘application/models’ (*Scapply*); ‘interaction’ (*Scintact*); ‘student investigations’ (*Scinvest*) and ‘hands-on activities’ (*Schands*). Students were asked ‘When learning <school science> topics at school, how often do the following activities occur?’. For all the four different teaching styles, the students were given the response alternatives ‘In all lessons’, ‘In most lessons’, ‘In some lessons’ and ‘Never or hardly ever’.

For the enjoyment of science (*Joyscie*) students were asked whether they ‘strongly agree’, ‘agree’, ‘disagree’ and ‘strongly disagree’ with five different statements pertaining to their enjoyment in ‘reading about’, ‘doing problems’ or ‘acquiring new knowledge’ in science. Six items make up the science activity scale (*Scieact*), with information about the frequency with which students, ‘watch TV programmes’, ‘borrow or buy books’ or ‘visit websites’ with focus on science, among others.

Parent Level Control Variables

For the control variables at the parental level we use five different scales: parents’ perception on environmental issues (*Pqenperc*), parents’ environmental optimism (*Pqenvopt*), parents’ view of the importance of science (*Pqscimp*), parents’ personal value of science (*Pqpersci*), and parents’ science activities at age 10 (*Pqsciact*). The parental variables *Pqenvopt* and *Pqenperc* were constructed in the same way as for students (see above). For *Pqgensci* parents were asked about their view about the general influence of science on society, covering aspects such as the economy or social benefits. For *Pqpersci*, parents were asked how science affects them personally in their daily life. In the final parent level index, *Pqsciact*,

⁸⁸ The ESCS index is comprised of five OECD-standardized indices: highest occupational status of parents (HISEI), highest educational level of parents (PARED), family wealth (WEALTH), cultural possessions (CULTPOS), and home educational resources (HEDRES). See OECD (2009) for additional information about the ESCS computation.

parents had to indicate how often ('very often', 'regularly', 'sometimes' or never') they read books, watched TV programs or visited website related to science at the age of 10, among others (for a full description of *Pqgensci*, *Pqpersci* and *Pqsciact* see Appendix II).

School Level Control Variables

We chose to include seven control variables at school level: school size (*Schlsize*), teacher student ratio (*Stratio*), proportion of certified teachers (*Propcert*), proportion of teachers with ISCED 5A level qualifications (*Propqual*), quality of educational resources (*Scmatedu*), responsibility for curriculum index (*Respcurr*) and teacher shortage (*Tcshort*). Having acquired an ISCED 5A level education corresponds to a post-graduate or tertiary degree.⁸⁹ *Stratio* was computed by PISA, by dividing the size of schools with number of teachers at the corresponding school and by weighting part-time teachers by 0.5 as compared to 1.0 for full-time teachers (OECD 2009). *Propcert* and *Propqual* were calculated by dividing the total number of certified and ISCED 5A qualified teachers respectively, with the total number of teachers at the school in question (OECD 2009).

The school variables *Scmatedu*, *Respcurr*, and *Tcshort* are PISA calculated scales and indexes. *Scmatedu* is computed from answers by school principals on seven items on whether school instruction is hindered by material shortage or school infrastructure inadequacies (see Appendix II). *Respcurr* is an index calculated on four items pertaining to the responsibilities at schools for 'Establishing student assessment policies', 'Choosing which textbooks are used', 'Determining course content', and 'Deciding which courses are offered' (OECD 2009). The final index is a calculated ratio between 'yes' answers from principals or teachers at schools compared to 'yes' answers from education establishment at the central level, where the higher values signify higher school autonomy in decision making in the item categories. *Tcshort* is a scale based on four items concerning lack of science, math, language teachers and other subject, to assess the school's capacity to operate.⁹⁰

⁸⁹ For Colombia, achieving an ISCED 5A level education was calculated by PISA to equal 15.5 years of schooling (OECD 2009).

⁹⁰ The *Tcshort* items were not inverted for scaling, thus, a higher WLE score reflects a higher degree of teacher shortage.

Table 5.1 Summary Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max	Scale Reliab.
Awareness of Environmental Issues (<i>Envaware</i>)	3956	-0.43	0.87	-2.58	1.77	0.74
Awareness of Renewable Technologies (<i>Retaware</i>)	3903	0.72	0.45	0.00	1.00	N/A
Responsibility for Sustainable Development (<i>Respdev</i>)	3956	0.08	0.70	-2.01	2.19	0.64
Environmental Optimism (<i>Envopt</i>)	3956	0.31	1.21	-1.61	2.85	0.87
Perception of Environmental Issues (<i>Envperc</i>)	3956	0.72	0.80	-1.60	1.39	0.79
Environmental Education	3956	0.32	0.88	-2.27	1.39	0.49
Female	3956	0.55	0.50	0.00	1.00	N/A
Age	3956	15.85	0.29	15.42	16.33	N/A
Native	3855	0.997	0.06	0.00	1.00	N/A
Economic, Social and Cultural Status	3951	-0.94	1.24	-5.03	2.32	0.73
Enjoyment of Science	3951	0.76	0.76	-2.15	2.06	0.85
Science Activities	3947	0.96	0.77	-1.69	3.38	0.76
Science Teaching – Application/Models	3879	0.56	0.97	-2.46	2.63	0.71
Science Teaching – Interaction	3904	0.36	0.81	-2.51	2.47	0.64
Science Teaching – Student Investigations	3872	0.63	0.92	-1.26	3.03	0.68
Science Teaching – Hands-on Activities	3885	0.28	0.90	-2.10	2.91	0.68
Parents Perception of Environmental Issues	3704	0.27	0.74	-6.21	0.68	0.71
Parents Environmental Optimism	3694	0.18	1.15	-1.09	2.93	0.91
Parents General Value of Science	3689	0.36	0.87	-3.29	1.73	0.77
Parents Personal Value of Science	3691	0.87	0.91	-3.25	2.30	0.73
Parents Science Activities at Age 10	3695	0.38	1.08	-2.27	3.33	0.67
Log School Size	3688	7.00	1.24	1.10	8.84	N/A
Log Teacher Student Ratio	3468	2.95	1.06	-1.02	3.74	N/A
Proportion of certified teachers	3408	0.89	0.28	0.00	1.00	N/A
Teacher Shortage	3912	0.10	1.11	-1.06	3.62	0.87
Proportion of teachers with ISCED 5A	3403	0.75	1.29	-25.19	1.00	N/A
Quality of Educational Resources	3956	-1.14	1.15	-3.43	2.14	0.89
Responsibility for curriculum index	3956	-0.20	0.78	-1.33	1.27	N/A

Source: Authors tabulations, based on PISA 2006 dataset.

Note: The values of Cronbach's alpha can be understood as high reliability (>0.80), moderate reliability (0.70-0.79), low reliability (0.60-0.69) and very low reliability (<0.60) (OECD 2007); N/A = Not applicable.

5.5 Empirical Analysis and Findings

In our cross-sectional sample, we are interested in predicting whether environmental education has an impact on environmental output measures using student-level and school-level characteristics. In order to analyze our multilevel data, we cannot use simple OLS regression models as hierarchically structured data violate standard linear regression assumptions. We have a two-level nested model, where the individual observations are nested within schools. Based on the maximum likelihood estimation method, we estimate a linear mixed model which

contains both fixed effects and random effects. The general matrix notation for our model is:

$$y = X\beta + Z\mu + \varepsilon$$

where y is an $n \times 1$ vector of responses, X is an $n \times p$ matrix containing the fixed effects regressors, β is a $p \times 1$ vector of fixed-effects parameters, Z is an $n \times q$ matrix of random effects regressors, μ is a $q \times 1$ vector of random effects, and ε is an $n \times 1$ vector of errors.

More specifically, our multilevel mixed-effects linear regression model allows for a random slope on our main explanatory variable, environmental learning (captured by u_{1j}) :

$$envaware_{ij} = \beta_0 + \beta_1 * envlearn_{ij} + u_{0j} + u_{1j} * envlearn_{ij} + \varepsilon_{ij}$$

Before the data analysis, we identify outliers on the dependent variables by assessing whether or not they fall within a set of numerical boundaries called ‘inner fences’ and ‘outer fences’. Extreme outliers, i.e., points beyond an outer fence, are dropped from the analysis. We also test the normality of our dependent variables and our main explanatory variable. Values for skewness and kurtosis between -2 and +2 are considered acceptable in order to prove normal univariate distribution (George and Mallery 2010).⁹¹ Kurtosis and skewness values below -3 and above +3 strongly indicate non-normality. The absolute values of the skewness and kurtosis for *Envedu* were -0.18 and 2.08 respectively, indicating no concern about the normality of data. Kurtosis and skewness values for our output measures are equal to 2.6 or below, indicating some concern about the normality of data. We also tested multicollinearity between the explanatory variable and the control variables (both individual and school level characteristics) with linear regression on the dependent variable. The variance inflator diagnostics were always below the threshold of 10, suggesting that collinearity does not affect the regression coefficients.

In order to empirically test whether environmental education has a positive impact on the environmental outcome variables (*Envaware* and *Retaware*), we run a base estimation controlling for environmental education only (Model 1). We then control for individual demographic control variables to the model (Model 2). In Model 3, we control for individual science abilities. Model 4 controls for parental characteristics and Model 5 controls for school-level variables. In all models, we

⁹¹ Meyers, Gamst and Guarino (2006) use a stricter threshold of ± 1.00 for both skewness and kurtosis.

specify the intercept to be random. Moreover, the random effects will be reported as variances rather than as standard deviations in all our models.

Model 1

In Table 5.2, we report the empirical results for our base specification. In this model we include our main explanatory variable environmental education. Column (1) reports the results for our first main dependent variable, environmental awareness. Column (2) does the same for our second main independent variable, awareness for RETs. Since awareness for RETs is a binary variable, we run a multilevel mixed-effects ordered logistic regression model for this specific dependent variable throughout the analysis. We also provide additional estimation results for three other environmental output measures (e.g. responsibility for sustainable development, environmental optimism, and perception of environmental issues) in columns (3)-(5). In each Table, we also report the number of observations, the Akaike information criteria (AIC) and the Bayesian information criteria (BIC) in smaller-is-better form as well as the deviance of each model, indicating how well the model fits the data.

Looking at the relationship between environmental awareness and environmental education first, we observe a strong positive and highly statistically significant relationship. A higher level of environmental education is associated with a higher level of environmental awareness. The strong and statistically significant relationship disappears, however, when we use awareness for RETs as dependent variable. We would like to remind the reader that *Retaware* was a sub-component of *Respdev*. When we use *Respdev* as dependent variable, the relationship becomes positive and statistically significant again. This suggests that even though environmental education may promote responsibility for sustainable development in general, it may not necessarily encourage awareness for renewable technologies.

Last, our model also predicts that more environmental education goes hand in hand with a decrease in environmental optimism. This finding would suggest that students who learn more about the environment at school acquire a more realistic (less optimistic) picture of our global ecosystem and recent environmental developments. All in all, the results displayed in Table 5.2 provide only some tentative evidence that environmental education promotes environmental literacy as the coefficient on environmental education is statistically significant in only three out of six cases.

Table 5.2 Environmental Education and Environmental Output Measures, Base Specification (Model 1)

	(1) Envaware	(2) Retaware	(3) Respdev	(4) Envopt	(5) Envperc
<i>Fixed Effects</i>					
Envlearn	0.07*** (0.03)	0.00 (0.05)	0.05*** (0.02)	-0.08* (0.04)	0.00 (0.02)
Intercept	-0.46*** (0.03)	0.94*** (0.05)	0.07*** (0.02)	0.34*** (0.04)	0.72*** (0.02)
<i>Random Effects</i>					
sd (Envlearn)	0.00 (0.02)	0.00 (0.14)	0.04 (0.04)	0.00 (0.00)	0.00 (0.00)
sd (Intercept)	0.31 (0.02)	0.29 (0.06)	0.11 (0.02)	0.38 (0.03)	0.15 (0.02)
sd (Residual)	0.81 (0.01)		0.69 (0.01)	1.14 (0.03)	0.78 (0.01)
<i>Model Fit Statistics</i>					
Deviance	9828.78	4650.64	8366.15	12493.99	9410.72
AIC	9833.52	4658.64	8376.15	12503.99	9420.72
BIC	9823.52	4683.72	8407.56	12535.40	9452.14
Observations	3956	3903	3956	3956	3956

Note: Standard errors are shown in parentheses. *** denotes significance at the 1% level, ** at the 5% level, * at the 10% level.

Model 2

In Table 5.3, we control for student background variables such as gender, age, immigrant status and economic, social and cultural status (ESCS). The gender and immigrant status variables are dummy-coded. With regard to the immigrant status, we distinguish between native students, first-generation students and second-generation students. Male and native students serve as reference group for the respective variables.

Compared to the results in Table 5.2, the positive effect of environmental education on environmental awareness has been reduced in magnitude and is no longer statistically significant when controlling for demographic factors at the student-level. Similar to the results presented in Table 5.2, we do not find empirical evidence for a strong relationship between environmental education and awareness of RETs. In this model, we also start addressing our third research question, namely to what extent individual-level characteristics determine environmental literacy.

Table 5.3 Environmental Education and Environmental Output Measures, Controlling for Personal Characteristics at Individual Level (Model 2)

	(1) Envaware	(2) Retaware	(3) Respdev	(4) Envopt	(5) Envperc
<i>Fixed Effects</i>					
Envlearn	0.04 (0.03)	-0.02 (0.05)	0.02 (0.01)	-0.04 (0.04)	-0.00 (0.02)
Female	0.00 (0.03)	-0.20*** (0.08)	-0.05** (0.02)	-0.03 (0.04)	0.20*** (0.03)
Age	0.13*** (0.05)	-0.13 (0.13)	-0.00 (0.04)	-0.06 (0.07)	0.07 (0.04)
Generation1	0.50 (0.58)	12.45 (505.73)	-0.39 (0.49)	0.30 (0.82)	0.34 (0.55)
Generation2	-0.45* (0.25)	-0.82 (0.64)	-0.17 (0.21)	0.51 (0.35)	-0.46* (0.24)
ESCS	0.13*** (0.01)	0.10*** (0.03)	0.06*** (0.01)	-0.10*** (0.02)	-0.00 (0.01)
Intercept	-2.36*** (0.73)	3.21*** (2.03)	0.19 (0.62)	1.19 (1.04)	-0.50 (0.70)
<i>Random Effects</i>					
sd (Envlearn)	0.00 (0.00)	0.00 (0.12)	0.01 (0.01)	0.00 (0.00)	0.00 (0.00)
sd (Intercept)	0.25 (0.02)	0.23 (0.07)	0.08 (0.02)	0.34 (0.03)	0.13 (0.02)
sd (Residual)	0.80 (0.01)		0.68 (0.01)	1.14 (0.01)	0.77 (0.01)
<i>Model Fit Statistics</i>					
Deviance	9441.90	4478.38	8049.06	12138.62	9040.66
AIC	9461.90	4496.38	8069.06	12158.62	9060.66
BIC	9524.46	4552.57	8131.63	12221.18	9123.23
Observations	3852	3805	3852	3852	3852

Note: Standard errors are shown in parentheses. *** denotes significance at the 1% level, ** at the 5% level, * at the 10% level.

Age is positively correlated with environmental awareness. However, we do not want to overemphasize the positive coefficient on age as the analysis only includes 15- and 16-year old students. What is however very interesting is the fact that native Colombian students (e.g. students who have at least one parent born in Colombia), tend to be more aware of environmental issues than second-generation immigrant students. Probably not very surprisingly, a higher socio-economic status coincides with a higher level of environmental awareness. The same is true when we use awareness for RETs as dependent variable. Once again, the coefficient on

ESCS is positive and highly statistically significant. While we did not find a significant relationship between gender and environmental awareness, we do so for awareness of RETs. The negative coefficient on female suggests that Colombian female students are less aware of renewable energy technologies if compared to Colombian male students.

Overall, the results displayed in Table 5.3 show that when controlling for individual-level demographic characteristics, environmental education is not statistically significant anymore regardless of the environmental output measure used. Gender is not only statistically significant when examining awareness for RETs, but it is also highly statistically significant when examining responsibility for sustainable development and perception of environmental issues. Our data suggests that women tend to feel less responsible for sustainable development than men but tend to have a stronger perception of environmental issues than men, *ceteris paribus*. The only variable that has sufficient explanatory power in all six specifications is the socio-economic status of the student. The higher the socio-economic status of a Colombian student the more concerned he/she is with environmental issues than those Colombian students that have low ESCS, *ceteris paribus*. This result can be interpreted as empirical support for the sociological theory of post-materialism (Inglehart 1977; Inglehart 1990; Inglehart 1997), whereby environmental awareness is strongly influenced by economic development at the country level and a higher socio-economic status at the individual level (see also Brechin 1999; Franzen 2003; Kidd and Lee 1997; Panayotou 1993; Panayotou 1997).

Model 3

Since “most environmental topics (e.g. photosynthesis, biodiversity etc.) and issues (e.g. biodiversity loss, habitat fragmentation etc.) have underlying scientific principles drawing from different science fields (e.g. chemistry or mathematics)” (Coertjens et al. 2010, 498), we also need to control for students’ science abilities (i.e. knowledge and skills). While previous studies aggregated science teaching methods scores (*Scintact*, *Schands*, *Scinvest*, and *Scapply*) for each school based on the indexes of science teaching methods at student level (Coertjens et al. 2010; Lin and Shi 2014), we do not aggregate the science ability indexes for each school but use those indices at the student level to test whether differences in the science ability of individuals have sufficient explanatory power (Table 5.4).

Table 5.4 Environmental Education and Environmental Output Measures, Controlling for Science Characteristics at Individual Level (Model 3)

	(1) Envaware	(2) Retaware	(3) Respdev	(4) Envopt	(5) Envperc
<i>Fixed Effects</i>					
Envlearn	0.07** (0.03)	0.07 (0.05)	0.04*** (0.02)	-0.07* (0.04)	-0.00 (0.02)
JoyScie	0.21*** (0.02)	0.15*** (0.05)	0.14*** (0.01)	0.02 (0.03)	0.10*** (0.02)
ScApply	0.07*** (0.02)	0.07 (0.05)	0.08*** (0.01)	-0.02 (0.03)	0.07*** (0.02)
ScIntact	0.08*** (0.02)	-0.00 (0.05)	0.07*** (0.02)	-0.11*** (0.03)	0.03* (0.02)
ScInvest	-0.07*** (0.02)	-0.01 (0.05)	-0.03** (0.01)	0.19*** (0.03)	-0.08*** (0.02)
ScHands	-0.66*** (0.03)	0.06 (0.01)	-0.08*** (0.02)	0.24*** (0.04)	0.67*** (0.02)
Intercept	-0.66*** (0.03)	0.77*** (0.06)	-0.08*** (0.02)	0.24*** (0.04)	0.67*** (0.02)
<i>Random Effects</i>					
sd (Envlearn)	0.00 (0.00)	0.00 (0.23)	0.06 (0.03)	0.00 (0.00)	0.05 (0.06)
sd (Intercept)	0.30 (0.02)	0.28 (0.06)	0.11 (0.02)	0.37 (0.30)	0.13 (0.03)
sd (Residual)	0.78 (0.01)		0.66 (0.01)	1.14 (0.01)	0.77 (0.01)
<i>Model Fit Statistics</i>					
Deviance	9281.62	4544.17	7884.39	12149.32	9059.50
AIC	9301.62	4562.17	7904.39	12169.32	9079.50
BIC	9364.21	4618.44	7966.99	12231.91	9142.09
Observations	3863	3838	3863	3863	3863

Note: Standard errors are shown in parentheses. *** denotes significance at the 1% level, ** at the 5% level, * at the 10% level.

When controlling for students' science abilities, environmental education has once again a positive and statistically significant effect on environmental awareness, but also on responsibility for sustainable development in general. Environmental education, however, does not have a significant influence on awareness for RETs. Like in Model 1, environmental education impacts environmental optimism negatively.

In five out of six cases, the coefficient on enjoyment of science is highly statistically significant and positive. Colombian students that tend to show a greater enjoyment of learning science are found to be more environmentally literate, holding all other factors constant. Our empirical findings are therefore in line with previous results by Littleldyke, (2008) who found a positive relationship between enjoyment of science and environmental attitudes.

All science ability variables are important in explaining student's environmental awareness. Students that report (i) a strong focus on model or applications in science teaching and (ii) higher levels of student interaction in their science lessons show higher levels of environmental awareness. Interestingly, higher levels of hands-on activities in science teaching and higher levels of student investigations are negatively correlated with environmental awareness. These results are very surprising and we do not have an intuitive explanation for those two findings at this stage.

With regard to awareness for RETs, we only find enjoyment of science to be (positive) statistically significant predictors. Awareness for RETs among Colombian students do not vary much based on the other student science abilities such as student interaction or student investigations. Another major observation is that several science abilities seem to negatively impact environmental optimism. More use of student investigation, more student interaction science teaching and a higher level on hands-on activities in science lessons tend to significantly lessen Colombian students' environmental optimism.

Model 4

Since families play a fundamental role in shaping students' attitudes, views and opinions about environmental issues, we also control for parent characteristics. The results are reported in Table 5.5. When examining environmental awareness, environmental education remains statistically significant at the 10 percent level.

Similar to the student science ability variables in Model 3, the majority of the parental variables have significant explanatory power. Parents' perception of environmental issues, parents' personal value of science and the level of science activities of parents at age 10 are positively correlated with students' environmental awareness. Parents' environmental optimism, however, is inversely related with students' environmental awareness and two other environmental output measures (responsibility for sustainable development and perception of environmental issues). Looking at awareness for RETs, we only find parents science activities at age 10 and parents personal value of science to be positive and statistically significant predictors. Surprisingly, the parents' view of the importance of science is negatively correlated with awareness for RETs. This results requires further investigation in the future because we do not have an intuitive explanation

for this finding. The coefficient on environmental education, in turn, remains statistically insignificant.

Table 5.5 Environmental Education and Environmental Output Measures, Controlling for Parents Characteristics at Individual Level (Model 4)

	(1) Envaware	(2) Retaware	(3) Respdev	(4) Envopt	(5) Envperc
<i>Fixed Effects</i>					
Envlearn	0.06* (0.03)	0.00 (0.05)	0.04** (0.02)	-0.03 (0.03)	-0.02 (0.02)
PqEnperc	0.07*** (0.02)	-0.00 (0.05)	0.04** (0.02)	-0.01 (0.03)	0.28*** (0.02)
PqEnvopt	-0.05*** (0.01)	-0.01 (0.03)	-0.03*** (0.01)	0.38*** (0.02)	-0.02** (0.01)
PqScimp	-0.00 (0.02)	-0.09* (0.05)	0.02 (0.01)	0.01 (0.02)	-0.00 (0.02)
PqPersci	0.05*** (0.02)	0.17*** (0.05)	0.08*** (0.01)	0.07*** (0.02)	-0.01 (0.02)
PqSciact	0.14*** (0.01)	0.15*** (0.04)	0.05*** (0.01)	-0.03* (0.02)	-0.00 (0.01)
Intercept	-0.55*** (0.03)	0.77*** (0.06)	-0.02 (0.02)	0.20*** (0.04)	0.68*** (0.02)
<i>Random Effects</i>					
sd (Envlearn)	0.00 (0.00)	0.00 (0.00)	0.06 (0.03)	0.00 (0.00)	0.00 (0.00)
sd (Intercept)	0.29 (0.02)	0.29 (0.06)	0.08 (0.03)	0.27 (0.03)	0.11 (0.02)
sd (Residual)	0.79 (0.01)		0.68 (0.01)	1.08 (0.01)	0.76 (0.01)
<i>Model Fit Statistics</i>					
Deviance	8818.52	4231.93	7569.15	10985.34	8328.47
AIC	8838.52	4249.93	7589.15	11005.34	8348.47
BIC	8900.49	4305.59	7651.12	11067.30	8410.43
Observations	3628	3583	3628	3628	3628

Note: Standard errors are shown in parentheses. *** denotes significance at the 1% level, ** at the 5% level, * at the 10% level.

When examining students' varying levels of environmental optimism and perception of environmental issues, we observe that the strongest predictors (in terms of magnitude) for the respective outcome variables are parents' environmental optimism (coefficient = 0.38) and parents' perception of environmental issues (coefficient = 0.28), respectively. Or put differently, a higher

level of parents' environmental optimism is associated with a higher level of environmental optimism among students. The same is true for perception of environmental issues. These effects are much greater than the parental impact on students' environmental awareness and awareness for RETs.

Our results confirm the notion that students often share their parents' views towards the environment. Parents that show a stronger environmental literacy and a stronger sense of responsibility towards environmental issues create an environment in which a child or student may feel more susceptible towards environmental issues. Our empirical findings do, however, also suggest that this relationship is much more pronounced with regard to feelings of optimism or general perceptions than with actual awareness or a sense of personal responsibility.

Model 5

In the previous models we have explored the relationship between environmental literacy and environmental education controlling for student-level characteristics. In Model 5, we will address our fourth research question by accounting for school-level characteristics. We investigate to what extent does the school 'infrastructure' (public versus private, school size, teacher-student ratio, teacher shortage, proportion of qualified/certified teachers, quality of educational resources, etc.) promote environmental awareness and awareness for RETs. The results are displayed in Table 5.6.

When controlling for school-level characteristics, environmental education no longer exerts a positive impact on environmental awareness. The negative and statistically significant coefficient on public schools suggests that, holding all other factors constant, students in Colombian public school have a lower level of environmental awareness if compared to students in Colombian private schools. At the same time, the quality of educational resources has a significant effect on environmental awareness. Since teacher shortage is measured on a negative scale, the negative coefficient on teacher shortage suggests that a teacher shortage impacts environmental awareness negatively, *ceteris paribus*: the higher the level of teacher shortage, the lower the level of students' environmental awareness. Our first tentative explanation for this result is that school classes that suffer from teacher shortage do not have adequate human resources to provide high quality instruction in all fields of education, including science and environment.

Table 5.6 Environmental Education and Environmental Output Measures, Controlling for School Characteristics at School Level (Model 5)

	(1) Envaware	(2) Retaware	(3) Respdev	(4) Envopt	(5) Envperc
<i>Fixed Effects</i>					
Env. Education	0.02 (0.03)	-0.01 (0.05)	0.03 (0.02)	-0.02 (0.04)	-0.01 (0.02)
Public	-0.23** (0.11)	-0.20 (0.17)	-0.08 (0.05)	0.15 (0.14)	0.02 (0.07)
Log School Size	0.05 (0.05)	-0.06 (0.08)	-0.02 (0.02)	0.09 (0.06)	-0.04 (0.03)
Log Student- Teacher Ratio	-0.06 (0.06)	0.02 (0.02)	-0.01 (0.03)	-0.03 (0.07)	0.01 (0.04)
Teacher Shortage	0.05* (0.03)	0.09* (0.04)	0.02* (0.01)	-0.07** (0.04)	0.04** (0.02)
Certified Teachers	0.17 (0.11)	0.06 (0.17)	0.05 (0.06)	-0.19 (0.14)	0.20*** (0.07)
Quality of Educat. Resources	0.06* (0.04)	0.07 (0.05)	0.04** (0.02)	-0.09** (0.05)	0.01 (0.02)
Curriculum	0.02 (0.04)	0.11* (0.06)	0.04* (0.02)	-0.01 (0.05)	0.02 (0.03)
Intercept	-0.49** (0.21)	1.52*** (0.36)	0.29*** (0.11)	-0.24 (0.28)	0.78*** (0.14)
<i>Random Effects</i>					
sd (Envlearn)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
sd (Intercept)	0.27 (0.02)	0.19 (0.09)	0.07 (0.02)	0.33 (0.03)	0.12 (0.02)
sd (Residual)	0.82 (0.01)		0.69 (0.01)	1.14 (0.01)	0.79 (0.01)
<i>Model Fit Statistics</i>					
Deviance	7553.95	3568.82	6427.38	9574.49	7240.74
AIC	7577.95	3590.82	6451.38	9598.49	7264.74
BIC	7650.20	3656.90	6523.63	9670.74	7336.99
Observations	3043	3003	3043	3043	3043

Note: Standard errors are shown in parentheses. *** denotes significance at the 1% level, ** at the 5% level, * at the 10% level.

The relationship between environmental education and awareness for RETs remains statistically insignificant even after controlling for school-level characteristics. The results in column (2) show that most school-level determinants of RET awareness are not statistically significant. The exception is the positive

coefficient on both teacher shortage and school autonomy ('curriculum'). Schools with lower levels of teacher shortage and schools with a higher autonomy in making decisions about curricula and assessments exert a positive effect on the students' awareness of RETs. Teacher shortage also has a significant negative impact on responsibility for sustainable development and perceptions of environmental issues. When using environmental optimism as output measure, we find the opposite: a higher level of teacher shortage is correlated with a higher level of environmental optimism.

Another variable that has some explanatory power is the quality of educational resources. It is significant in three out of six cases. A better quality of educational resources is not only associated with a higher level of environmental awareness but also with a higher responsibility for sustainable development and a more pessimistic environmental outlook.

5.6 Discussion and Concluding Remarks

The overarching objective of this chapter has been to contribute to the knowledge of how to reduce the impact of the rebound effect and generate a potentially positive framework condition for RETs adoption. By focusing on what effect environmental education can have on generating environmental awareness in 15-year olds in a developing country, the aim has been to contribute to widening the knowledge pertaining to these broader sustainability challenges.

To summarize, we found weak evidence that environmental education can promote a higher level of environmental awareness. This is not the case for RETs awareness, however. Moreover, the empirical analysis above indicates that the determinants of environmental awareness and awareness for RETs vary significantly. Our results also suggest that there seem to be more reliable predictors for environmental awareness than for awareness of RETs. In general, the socio-economic status, stronger student science abilities, several parent characteristics and a few school-level characteristics such as quality of education resources and school ownership (public versus private) seem to be decisive factors for varying levels of environmental awareness among students in Colombia.

Our results have shown that, depending on which environmental output measure is chosen, both individual-level variables and school-level variables had similar and different effects on environmental literacy. The most robust explanatory variables in understanding different levels of environmental literacy were the students' socio-economic status (significant in five out of six cases), students' enjoyment of science (significant in five out of six cases), hands-on activities in science lessons (significant in all six cases), parents' science activities at age 10 (significant in five out of six cases) and teacher shortage (significant in five out of six cases).

Several other parental and science ability characteristics appeared to have an impact on specific environmental output measures. Overall, a stronger environmental knowledge through students' parents and science lessons taught in school tend to promote a higher level of environmental awareness while also contributing to a less optimistic outlook. In contrast, other individual student-level factors such as gender or immigration status or other school-level variables such as school ownership, school size or student-teacher ratio appear to have little influence on environmental literacy in Colombia. All in all, we do not find systematic empirical evidence that school-level characteristics 'trump' student-level characteristics in explaining students' environmental awareness, attitudes, optimism or perception. Environmental awareness, beliefs and attitudes do not develop/exist in isolation. Environmental literacy is shaped through the family environment, the socio-economic status, environmental education, the school 'infrastructure' and several other factors. Our study supports Kollmuss and Agyeman (2002) theoretical viewpoint that both internal and external factors encourage enhanced environmental literacy.

The empirical results presented in this chapter suggest that environmental education should not be considered a silver bullet in promoting environmental literacy among young people. This does not mean that schools should reduce their efforts in emphasizing and promoting environmental education at school. Schools can to some extent promote more pro-environmental attitudes in their students in both developed countries (Coertjens et al. 2010; Lin and Shi 2014) and in developing countries (this chapter). We do, however, conclude that strengthening environmental education in school curricula is a necessary but not sufficient condition for improving environmental awareness among the youth. Since a child spends most time with, and learns from, parents in a particular socio-economic environment, parents do play a crucial role in the environmental education of their child. Moreover, since several developing countries may either lack the human resources, or the financial resources (or both) to effectively improve the quality and quantity of environmental education in school curricula, environmental literacy must be supported with both national and global political leadership.

While the study provides a number of insights, there are limitations. First, even though PISA data offers a wide range of student information, PISA assesses only a limited amount of what is actually taught in schools and collects very little data on the role and contribution of teachers (see also Mortimore 2009). Second our study uses cross-sectional data which prevents us from analyzing the impact of environmental education on environmental output measures over time. Third, our multilevel analysis does not allow for causal inferences. Even in those cases where *Envaware* and *Envedu* are positively correlated, we do not know the direction of influence and we cannot rule out the possibility that causality could run both ways. Fourth, our model did not account for potential regional differences across Colombian schools. As discussed above, environmental literacy could vary

significantly depending on whether (i) the school is located in a rural or urban area, and (ii) whether the students live in an urban or rural context.

Our empirical results call for further research. Future research studies should investigate to what extent the impact of environmental education on environmental awareness and RETs varies between different developing countries. Another interesting research question is to what extent environmental education can induce a change in behavior and attitudes towards environmental issues over the long-run. Moreover, research that investigates to what extent environmental education aimed at children can influence environmental literacy of parents is still at its infancy (see Damerell, Howe, and Milner-Gulland 2013). Lastly, in line with Coertjens et al. (2010), more international comparative research is vital to test our and previous results in other educational, cultural, social and economic settings.

Chapter 6. Framework Conditions of Technological Transition: Re-thinking the Boundary for a Technological Innovation System

6.1 Introduction

The integral activities of a technological transition have been studied to great length in the technological innovation systems' literature, resulting in several lists of processes or 'functions' deemed essential for the generation, development, diffusion and utilization of a new technology (Johnson and Jacobsson 2001; Edquist 2005; S. Jacobsson and Bergek 2006; Hekkert et al. 2007). These lists of functions have been both developed and empirically tested in high-income industrialized countries such as Sweden, the Netherlands and Germany (Negro, Hekkert, and Smits 2007; Negro, Suurs, and Hekkert 2008; Negro and Hekkert 2008; Hillman et al. 2008). By making certain adjustments to the lists of functions (Chapter 3), the TIS function approach, initially developed for high-income industrialized nations, has also been used for empirical analyses of technological adoption in low and middle-income developing countries (e.g., Chapter 4 of this thesis; van Alphen, Hekkert, and van Sark 2008).⁹²

While these integral activities of the inner workings of the technological system have received much focus in the analysis of technological innovation and in helping delimit the system, certain aspects of the contextual setting in which a technological sector operates have received less attention. With the exception of institutions, other socio-political contextual factors or framework conditions, have been regarded as external factors, and consequently insufficiently mapped as part of the system. While several authors (e.g., Hekkert and Negro 2009; S. Jacobsson and Bergek 2006) have raised the potential relevance of these external factors, they have not been analyzed in an explicit and systematic manner. Moreover, when mentioned in previous TIS literature external factors have been predominately discussed in the context of high-income countries. There is scattered reporting in the literature on renewable energy diffusion in developing countries of the influence of external factors, but this has not been sufficiently synthesized nor

⁹² This chapter uses the income classification (GNI per capita) by the World Bank. For the fiscal year of 2017, low-income economies are those of \$1,025 or less in 2015; lower middle-income economies are those between \$1,026 and \$4,035; upper middle-income economies are those between \$4,036 and \$12,475; high-income economies have a GNI per capita of \$12,476 or more (The World Bank 2016b).

conceptualized to allow for a systematic analysis of how these factors may influence technological innovation.

In an attempt to develop a comprehensive framework for analyzing technological change in developing countries, Chapter 3 took one step towards explicitly including a number of external factors to complement the TIS function analysis. By taking a step back from the technological innovation systems approach (Ch. 3 and 4), and instead discussing technological innovation from a wider systems perspective, this chapter aims to specifically advance the knowledge about the number and type of possible framework conditions, and whether they should be considered endogenous or exogenous to the system. In order to avoid confusion, *framework conditions* will predominately be used in this chapter to describe ‘external’ or contextual factors. More specifically, by placing focus on socio-political framework conditions, the aim of the chapter is to: 1) identify relevant framework conditions and how these conditions may vary for countries of different income category; 2) discuss in what ways these framework conditions may influence the system; 3) contribute to the debate about the boundaries within the systems of innovation approach, i.e., where the boundary of the system should be drawn; and 4) discuss the implications that framework conditions can have on policy.

Section 6.2 will review some early developments and use of systems. This will be followed by a discussion of the background, key concepts and remaining challenges of the systems of innovation approach (section 6.3). In section 6.4, data from previous empirical studies concerning framework conditions from countries of different income categories will be reviewed. Based on the results from these theoretical and empirical sections, reflections on the implications for the boundaries of systems in developing and high-income countries will be carried out in section 6.5. Section 6.6. will conclude.

6.2 Using Systems Thinking for Studying Innovation

A systems approach has been increasingly used in the last decades to analyze the complexity and the nonlinearity in response to policy interventions resulting from feedback loops in the context of innovation (Edquist 1997). As can be derived from its name, the Technological Innovation System Approach focuses on the generation, diffusion and utilization of a technology (Carlsson and Stankiewicz 1991). Other innovation systems such as Sectoral Innovation Systems (SIS) (Breschi and Malerba 1997) and Regional Innovation Systems (RIS) (Cooke, Uranga, and Etxebarria 1997; Saxenian 1994) have been used to analyze innovation activities in a specific sector or region.

The most common of the different innovation systems is the National Innovation Systems (NIS) approach. The concept of national systems of innovation was first

expressed by Christopher Freeman (1987) in a combined analysis of Japan’s economic and technological policy and development. Besides Freeman, the NIS was also discussed as a concept and developed by Nelson (1993) and Lundvall (1992). The definition of what makes up an NIS differs slightly between the authors, but their concepts still share several central elements, also with the Technological Innovation System (TIS) approach, namely the focus on technological innovation and the importance of institutions (Edquist 1997) (Table 6.1).

Table 6.1 Definitions of Systems of Innovation

NIS		TIS
<i>Freeman (1987)</i>	<i>Lundvall (1992)</i>	<i>Carlsson and Stankiewicz (1991)</i>
“the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies” (Freeman 1987, 1)	Broad Definition: “all parts and aspects of the economic structure and the institutional set up affecting learning as well as searching and exploring” (Lundvall 1992, 13)	“a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology” (Carlsson and Stankiewicz 1991, 94)

Source: Author, based on literature as presented in table.

6.3 Where to Draw the Line?

One key aspect that is unclear in the discussion about innovation systems is what specifically defines the system. In other words, what should be included in the system and what should be left out? Lundvall (1992) argued for a flexible approach to deciding what processes to consider in a system. In a context of technological transition, the boundary of the system may be regional, national or even global, thus providing an exact definition of what makes up the system becomes a challenge.

Charles Edquist (1997, 14) solves the issue of specifying the system by defining it as being “all important economic, social, political, organizational, institutional, and other factors that influence the development, and use of innovation”. Edquist (1997, 14) motivates this broad and comprehensive definition by stating that “important determinants cannot be excluded *a priori* if we are to be able to understand and explain innovation”. Edquist (1997, 15) continues to recognize the monumental task of identifying all the determinants that make up the innovation system adding that “we might never be able completely to identify the determinants of innovation”.

6.3.1 Categories of Determinants for a Systems of Innovation Approach

Following Edquist's (1997) suggestion of specifying the boundary of a system based on its determinants, i.e., what helps the system achieve its purpose, a systematic analysis of potential candidates is necessary. Categorizing determinants in a structured manner can also serve as an important tool in the process of identifying what makes up the system, and what is irrelevant for the system to realize its objective. A first step to categorizing the determinants of innovation is differentiating *integral components and activities* from *framework conditions* of the system.

Integral Components and Activities

From a Systems of Innovation (SI) perspective, integral components that shape the formal structures of the system are a set of actors collectively denoted organizations. These actors can include firms, universities and private and/or public agencies that are engaged in the innovation activities of the system in question, with a strong focus on learning.⁹³

In the TIS literature, activities that are considered to constitute the integral processes or functions⁹⁴ of a technological system have been identified and empirically analyzed. The collection of these integral activities⁹⁵ has been referred to as the *focal system* of technological innovation.⁹⁶ A focus on these integral activities as the principal activities of the system has resulted in a delimitation of the system, where these functions are considered endogenous to the system, while factors outside of the focal system are regarded as exogenous (Bergek et al. 2015). As put by Hekkert and Negro (2009, 592) "the [TIS] approach focuses strongly on activities endogenous to the innovation system, rather than exogenous factors". While the relevance of these integral functions has been shown in previous literature, what is less clear is whether the focal system alone should delimit the

⁹³ Liu and White (2001) based their framework consisting of five activities on earlier research, namely: R&D, implementation, end-use, education, and linkage.

⁹⁴ One example of a list of functions includes: entrepreneurial activities; knowledge development; knowledge diffusion; guidance of the search; market formation; resource mobilization; and legitimacy creation (Hekkert et al. 2007).

⁹⁵ Note that 'functions' and 'activities' are variations in terminology from different strand of literature that essentially describe the same aspect, namely integral processes an innovation system. For example, in the statistical measurement literature, such as the third version of the Oslo Manual, key processes for developing and implementing innovations are referred to as *innovation activities* rather than *functions* (OECD/Eurostat 2005).

⁹⁶ See also Chapter 2 (page 13) for additional discussion concerning definitions of the focal system.

system. In other words, if there are additional determinants of the system that are not part of the integral functions, should these be considered endogenous to the system?

Framework Conditions

The other form of system determinants, and the main focus of this chapter are framework conditions. As shown in Table 6.1, since the origin of systems of innovation, institutions have been considered a central framework condition to the approach. While the term institutions has been used differently by various authors⁹⁷, this chapter will draw on Edquist and Johnson's definition of institutions as "sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups" (Edquist and Johnson 1997, 46). Edquist (2005) later extended the definition of institutions to also include the regulation of the links between organizations. Depending on the make up, quality and effectiveness of these institutions, they can provide driving or constraining conditions for technological transition.

It can also be useful to separate institutions into *formal* and *informal*, where formal institutions are e.g., "constitutions, laws, property rights," and informal refers to norms in society such as "sanctions, taboos, customs, traditions, and codes of conduct" (North 1991, 97). While the SI literature has traditionally conceptually and implicitly considered institutions as an integral framework condition for technological transitions, a systematic integration of the different aspects of institutions, particularly *informal institutions*, into the SI approach for empirical analyses, represents a research gap.

Beyond institutions, there are other framework conditions, such as sociopolitical and economic factors, that may constrain or drive technological transition, and that thus far have been largely overlooked, or at least "not conceptualized in a formal way" (Hekkert and Negro 2009, 592). The relevance of considering additional sociopolitical and economic framework conditions has been emphasized in another approach, namely the Multiple-Level Perspective (MLP). By including in this heuristic approach, a socio-technical landscape analysis of technological transitions, authors have more consistently raised the potential influence of factors such as "oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems" (Geels 2002, 1260) or "growing environmental awareness" (Smith, Voß, and Grin 2010, 441). The MLP

⁹⁷ For example Lundvall (1992) mostly follows the definition of Douglas North (1991) by referring to institutions as the 'rules of the game', while Nelson and Rosenberg (1993) refer to institutions more as different types for organizations.

literature represents one important strand of research that can support the Systems of Innovation approach to identify and systematically incorporate important framework conditions that may constrain or drive technological transitions.

6.4 Reviewing the Evidence – A Comparative View of Framework Conditions

Following Edquist's (1997, 14) broad definition of what specifies a system, this section will review previous empirical case studies across different income categories, in order to identify framework conditions that can be considered determinants for a system of innovation, and how these may differ between developing and developed countries. Moreover, an analysis of how the identified framework conditions influence and interact with the focal system will be conducted.

6.4.1 Overview of Framework Conditions

This section provides a comparative review of eleven studies, involving in total 24 countries of different income categories. All studies have considered various framework conditions in their analyses of technological transitions, specifically addressing the adoption of renewable energy technologies (RETs) (Table 6.2). In total, summarized over the eleven studies, 17 different framework conditions were mentioned (Table 6.3). It should be emphasized that the framework conditions included in the different studies are influenced by the design of the study. Moreover, the studies analyzed do not represent an exhaustive list of studies considering framework conditions.⁹⁸ In that respect, there may be additional framework conditions that influenced the adoption of RETs in any of the countries that are not visible due to the design of the study, or that are considered in omitted studies. The purpose of this comparative literature review is not to produce a conclusive list of framework conditions, but rather to provide an initial indicative overview of relevant framework conditions acting in countries of different income categories.

⁹⁸ The studies were selected through a Boolean search with several combinations of the following keywords: renewable energy, transitions, (non-technical) barriers, technological innovation, and technological change. Two additional criterions were then applied, i.e., that the papers would address factors of technological change beyond the integral actors and activities, and that the selection of case studies included at least one country from each income category.

Table 6.2 List of Studies Included

#	Country	Income Level	Title	Author(s)	Year
1	Germany and the Netherlands	H	Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims	Marko P. Hekkert, Simona O. Negro	2009
2	USA	H	The cultural barriers to renewable energy and energy efficiency in the United States	Sovacool	2009
3	USA	H	Nontechnical Barriers to Solar Energy Use: Review of Recent Literature	R. Margolis and J. Zuboy	2006
4	Germany	H	Institutional dynamics and technology legitimacy – A framework and a case study on biogas technology	Jochen Markard, Steffen Wirth and Bernhard Truffer	2016
5	Colombia	UM	Identifying Barriers to Wind Energy Diffusion in Colombia: A Function Analysis of the Technological Innovation System and the Wider Context	Edsand, Hans-Erik	2017
6	Bangladesh, China, Laos, Mongolia, Nepal, Sri Lanka,	LM and UM	A qualitative factor analysis of renewable energy and Sustainable Energy for All (SE4ALL) in the Asia-Pacific	Benjamin K. Sovacool	2013
7	Morocco and the Philippines	LM	Driving force or forced transition? The role of development cooperation in promoting energy transitions in the Philippines and Morocco	Jens Marquardt, Karoline Steinbacher, Miranda Schreurs	2016
8	Nigeria	LM	Transitions in unlikely places: Exploring the conditions for renewable energy adoption in Nigeria	Olufolahan Osunmuyiwa and Agni Kalfagianni	2016
9	India	LM	Determinants of success and failure of community based micro hydro projects: In: Proceedings of the Energy and Climate Change in Cold Regions of Asia Seminar	Ete, M., Prochaska, F.	2009
10	Pakistan	LM	Identifying and addressing barriers to renewable energy development in Pakistan	Umar K. Mirza, Nasir Ahmada, Khanji Harijan, Tariq Majeed	2009
11	Kenya, Tanzania, Uganda	L and LM	Review of solar PV policies, interventions and diffusion in East Africa	Hansen, Ulrich Elmer Pedersen, Mathilde Brix Nygaard, Ivan	2015

Note 1: H (High-Income); UM (Upper Middle-Income); LM (Lower Middle-Income); L (Low Income)

Note 2: Edsand (2017) is also Chapter 4 of this thesis.

Table 6.3 Authors and List of Framework Conditions

Framework Conditions Considered	Studies (Authors)
1 Other Sector Influence	Hansen et al., 2015; Markard et al., 2016
2 International Donors	Hansen et al., 2015; Marquardt et al., 2015
3 International Market Price for RETs	Hansen et al., 2015
4 National or Regional Income	Osunmuyiwa and Kalfagianni, 2016
5 Change in Affluence	Hansen et al., 2015;
6 Income Distribution	Ete and Prochaska, 2009
7 Change in Population Size	Osunmuyiwa and Kalfagianni, 2016; Sovacool, 2013
8 Geography	Hansen et al., 2015; Sovacool, 2013
9 Unequal Access to Quality Education	Edsand, 2017
10 Access to Skilled Labor	Hansen et al., 2015; Ete and Prochaska, 2009; Mirza et al., 2009; Sovacool, 2013; Margolis and Zuboy, 2006
11 Armed Conflicts	Sovacool, 2013; Edsand, 2017
12 Corruption	Edsand, 2017
13 Economic Growth	Hansen et al., 2015; Sovacool, 2013; Edsand, 2017
14 Culture	Sovacool, 2009
15 Environmental Awareness	Edsand, 2017
16 Awareness for RET	Mirza et al., 2009; Sovacool, 2013; Margolis and Zuboy, 2006
17 Climate Change	Sovacool, 2013; Edsand, 2017; Hekkert and Negro, 2009

Note: Edsand (2017) is also Chapter 4 of this thesis.

To start, it is important to clarify a few definitional aspects of the framework conditions identified in the case studies (Table 6.3). *Other sector influence* refers to potential influence by other RETs sectors and/or any other non-technical sectors on RET adoption. Economic issues are addressed differently and at different levels (e.g., household vs. national) in the various case studies. U. E. Hansen, Pedersen and Nygaard (2015), for example, refer specifically to a change in the *affluence* of households. Osunmuyiwa and Kalfagianni (2016) analyze the influence of regional or national income on RET adoption in Nigeria. The denotation *National or*

Regional has been added to differentiate it from changes in household income or affluence. National or Regional income is strictly concerned with monetary influence, i.e., the amount of the money available for investments. *Economic Growth* is the economic rate of change, which encompasses both positive and negative growth (e.g., financial crisis).⁹⁹ Income distribution (Ete and Prochaska 2009) is related to affluence, as both influence a household's monetary strength. However, it is different from affluence in that it refers to the underlying structural aspect of income distribution and salary composition, and should therefore be considered a separate framework condition. *Unequal Access to Quality Education* is separated from *Access to Skilled Labor*, as the former refers to a structural framework condition relating to the national education system.

Finally, while *culture* is not for measurement purposes explicitly defined, Sovacool (2009, 366) divides the analysis of culture and its influence on RET adoption and energy efficiency in three categories, namely: “public apathy and misunderstanding, conceptions of consumption and abundance, and psychological resistance”. Culture and informal institutions are interrelated but are not equivalent. Culture can help shape informal institutions (Helmke and Levitsky 2004). Therefore, they are treated as a separate framework conditions.

Specific *awareness for RET* and the more general *environmental awareness* are treated as two separate framework conditions, with the latter going beyond awareness about a particular technology. Considering *environmental awareness* as a framework condition allows for a wider analysis of the potential influence of a change in environmental awareness on a society's position on sustainability issues, such as a country's choice of sources of energy generation.

6.4.2 Framework Condition Influence on RETs Adoption

A comparative analysis of the framework conditions considered in the case studies reveals both differences and similarities across the various income-categories (Table 6.4). In total, there are 12 framework conditions that are only considered in studies for developing countries, while one framework condition was exclusively considered in the high-income category. Influence from four framework conditions were considered in both developed and developing country studies, namely, *Other Sectors*, *Access to Skilled Labor*, *Awareness for RET* and *Climate Change*. For the mixed study by Sovacool (2013), involving a comparative review of one upper-middle (Malaysia) and nine lower middle-income Asian-Pacific countries, Table

⁹⁹ See e.g., Geels (2013) for a discussion on the potential influence of a financial-economic crisis on ‘sustainable transitions’.

6.4 simply indicates if a framework condition was mentioned in one or more of the included countries.

Table 6.4 Framework Conditions Influence on Adoption of RETs

	Developing Countries										Developed Countries			
Country	Tanzania	Uganda	Kenya	Morocco	Philippines	Nigeria	India	Pakistan	Multiple ¹	Colombia	GER and NED	USA	USA	Germany
Income Level	L	L	LM	LM	LM	LM	LM	LM	UM	UM	H	H	H	H
Framework Conditions														
Other Sectors	+	+	+											+ -
International Donors	+	+	+	+	◊									
Reduced International Market Price for RETs	+	+	+											
National or Regional Income						◊								
Change in Affluence			+											
Income Distribution							-							
Change in Population Size						◊			1					
Geography	-		+						1					
Unequal Access to Quality Education										-				
Access to Skilled Labor			*				-	-	1				-	
Armed Conflicts									1	+ -				
Corruption										-				
Economic Growth			+						1	+				
Culture												-		
Environmental Awareness										◊				
Awareness for RET								-	1				-	
Climate Change									1	+	+			
+	Positive Effect on RET Adoption													
-	Negative Effect on RET Adoption													
+ -	Dual Effect													
◊	Little or no effect													
*	Measures taken eliminating negative effect													
1	Effect mentioned (Positive or Negative) in one or more of the 10 case studies													

Source: Author tabulation, based on analysis of included list of studies and framework conditions.

Again, since the frameworks or approaches for the studies vary, it is not possible to infer definite conclusions concerning relevant framework conditions in developing and developed countries. However, as Table 6.4 shows, authors designing studies that analyze barriers to RETs adoption in developing countries appear more concerned about a plurality of framework conditions. An explanation regarding the direction of the influence (positive or negative) follows.

Driving or Obstructing Framework Conditions

As can be deduced from Table 6.4, framework conditions can have a positive effect, i.e., drive technological transition forward or act as a negative effect obstructing the adoption of RETs. For example in Tanzania, Uganda and Kenya, the Information and Communication (ICT) sector, particularly through an expansion in mobile phone usage, positively influenced the adoption of solar Photovoltaic (PV) technology (Hansen, Pedersen, and Nygaard 2015). A decrease in international market price for RETs, along with international donor support also represent framework conditions that have driven the expansion of RETs in Tanzania, Uganda and Kenya. An interesting contrasting effect of international donor support was found between Morocco and the Philippines. While donor support had a limited effect in the Philippines, in Morocco, international donor

support, through policy advice, helped drive forward new initiatives for solar and wind projects, along with the incorporation of RETs in the Moroccan national energy strategy (Marquardt, Steinbacher, and Schreurs 2016).

Access to skilled labor was unanimously regarded as an obstructing framework condition across all studies that included this condition in the analysis. In the case of Kenya, developing specialized technical training, with the support of international donor assistance, into the analyzed solar PV project mitigated an expected negative influence from the limited access to skilled labor. The structural framework condition of unequal access to quality education was only specifically tested in Colombia (Chapter 4), where low access to quality education in remote rural areas was described as one of the most important reasons for the limited availability of skilled labor in these areas, which consequently negatively affected decisions for initiating new RETs projects. The only other study that relates a framework condition to the access to quality education is the Asia-Pacific comparative study (Sovacool 2013), by referring to the influence of literacy rates amongst rural villagers in Sri Lanka, Indonesia and Papua New Guinea. Low literacy rates in Indonesia and Papua New Guinea were found to be an obstructing factor for project dissemination, while higher literacy rates in Sri Lanka was described as a facilitating factor. In the study and in Table 6.3, low literacy was included under *access to skilled labor*, however *Unequal access to quality education* can provide an alternate structural explanation for the low skills in rural Indonesia and Papua New Guinea.

Other findings from Sovacool (2013) include a positive influence of population density in Bangladesh and China, compared to disadvantage of the smaller populations in Papua New Guinea and Malaysia. Geography and natural endowments have strongly influenced the adoption of various RETs, e.g., hydroelectric systems in mountainous Nepal and Sri Lanka, or solar energy in Papua New Guinea and Indonesia. Armed conflicts obstructed planned projects in both Nepal and Sri Lanka, slowing down the adoption of RETs. Awareness for RETs was considered an important ingredient for a successful implementation, and countries that spent time and resources marketing and spreading information about RETs saw a positive effect on adoption. Climate change was generally found to create (positive) pressure on key actors (e.g., governments) to take action and initiate RETs projects, while a negative economic growth as a result of the global financial crisis increased the cost of RETs materials, which had a negative effect on RET adoption.

Dual Influence

Two of the studies found a dual effect from framework conditions, i.e., they had a driving and obstructing effect on RETs adoption. For example, the study by Markard, Wirth and Truffer (2016) showed how the agriculture sector in Germany

positively influenced the development of biogas technology at its genesis. The authors explain this positive relationship by a positioning of the biogas technology as beneficial to the agricultural sector, which gave legitimacy to the new technology. In a later and more expansive stage of biogas technology, the relationship with the agriculture sector was re-framed into a competitor role, as a consequence of increasing farming for energy production instead of food production. This conflict with the agriculture sector contributed to a loss in legitimacy for biogas in Germany, negatively affecting the technology.¹⁰⁰

Another form of dual influence was found with the armed conflict in Colombia, where the framework condition proved obstructive for one type of technological innovation, while driving another one forward. As shown in Chapter 4, armed conflict was found to have an obstructing effect on large wind parks in Colombia. Interestingly, the armed conflict simultaneously drove small-scale innovations of RETs, as the Colombian military required renewable energy solutions to aid soldiers in the field.¹⁰¹ As a consequence, by investing military funding in contracts with research institutes in Colombia, small-scale solar and wind innovations have emerged.

While the framework conditions can directly influence the integral components and activities of the system (focal system), e.g., armed conflicts blocking or slowing down RETs projects, framework conditions can also have an indirect impact on the focal system through an interaction with existing institutions. The interactions between FCs and institutions will be explained next.

Framework Conditions Interaction with the Focal System

When discussing how the various framework conditions influence the focal system, institutions become a central part of the story. In a general sense, since institutions constitute the “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, 46), actors relevant to the RET will always, in one way or another be affected by the institutions of the country in question. How framework conditions influence the focal system through interactions with institutions is perhaps less clear. In order to discuss the dynamics between framework conditions (FC) and institutions (North 1991), it is proposed to divide the FC in six different categories, namely, *modifying*, *structural*, *secondary*,

¹⁰⁰ The conflict between food production and the bio-fuel energy sector is not isolated to Germany. The production of grains or maize for fuel consumption for cars in high-income countries has contributed to price increases for food in developing countries.

¹⁰¹ Based on fieldwork in Colombia (see Chapter 4).

internal, multilevel, and natural (see Fig. 6.1). Armed conflicts, corruption, other sectors, and climate change are considered *modifying* FC because they influence the focal system by repositioning or modifying existing institutions. As a result, the institutional set-up can become better or worse aligned with the needs of the focal system, which was the case of Germany (Markard, Wirth, and Truffer 2016), where another sector (agriculture) helped modify the institutional set-up for biogas technology. Another example of the dynamics between FC and institutions is corruption. Corruption negatively influences the quality of national institutions, reducing the efficiency of focal system. The various types of interactions between different FC and institutions (formal and informal) are graphically depicted in Figure 6.1.

The *structural* category refers to FCs that are a result of the current institutional set-up, e.g., exclusive and elitist institutions will create structural inequality, including income inequality and unequal access to quality education. Access to skilled labor and changes in affluence are regarded as derivatives of structural FCs, hence the label *secondary* FCs. National and regional income and changes in population size also fall into the *secondary* FC category. Changes in National or Regional income are a product of economic growth and the institutional set-up, e.g., distribution of wealth through taxes. A change in population size is a product of multiple factors, such as migration (urbanization), economic and social development of a region.

Following North's (1991) definition of institutions, culture, environmental and RET awareness can be considered *internal FCs*, or as part of the existing informal institutions. Current *internal FCs* can directly influence the focal system; for instance, environmental awareness can play a role in the willingness of decision makers to invest in RETs. Changes in *internal FCs* can overtime induce modifications in the formal institutions that have a stake in the focal system. Following the environmental awareness example, increased environmental awareness can result in changes in policy makers' attitudes towards RETs and that in turn result in policy changes.

Figure 6.1 Framework Condition (FC) Interaction with Institutions

Source: Author.
Note: This graph aims to depict the different way that FC can interact with institutions. Wavy arrows indicate ongoing change within National Institutions due to FC interaction; the bold gray arrow on the right side of the figure indicates final institutional alteration influencing focal TIS, after interaction between FC and existing institutional setup has occurred.

Certain FCs, such as international donor support, changes in international RETs’ market price, climate change and economic growth interact with institutions at the global level, and thus transcend the national system and consequently the domestic institutions. Finally, the *natural* FCs refers to geography, which provides a set of national endowments, obstructing or driving RETs adoption.

It must be noted that the focal system can also influence institutions and certain framework conditions, e.g., German Biogas Technology on the agriculture sector. However, as the aim of Figure 6.1 is to depict how different framework conditions interact with institutions, the focal system influence on institutions and FCs factors is not shown here. The direct influence that the focal system has on institutions and framework conditions contributes to the multiple positive and negative feedback loops within the system and to the non-linearity of response to policy interventions.

6.5 Implications for the Boundary of the SI Approach

Following the strategy proposed by Edquist (2005; 1997) to delimit the system based on its determinants, the majority of framework conditions would consequently be considered endogenous to the system. This would in turn have implications for the boundary of the system. This chapter has shown that there are multiple framework conditions that help shape the trajectory of RET adoption in countries across income categories. The analysis of the empirical studies suggests that there are generally more framework conditions influencing (positively and/or negatively) the adoption of RETs in developing countries than in high-income countries (Fig. 6.2).

Figure 6.2 System Boundaries for Developing and Developed Countries

Source: Illustration by author.

Note 1: The dotted circle and arrows indicate a potential reduction in the size of the dynamic outer boundary, as a developing country shifts to a higher level of development.

Note 2: Figure 6.2 is illustrative based on the framework conditions considered in the included studies. It is not an exhaustive depiction of possible framework conditions.

However, in both developed and developing countries it is useful to view the system boundary as made up of several levels. In the case of high-income countries the delimited system includes an *inner* and *outer* boundary. The *inner* boundary includes the integral elements and activities, defined in the TIS literature as the functions of the technological system. The *outer* boundary fully delimits the system by including the framework conditions that influence the trajectory of the system.

For developing countries, it is proposed that delimiting the system requires a third level, referred to here as the *dynamic outer boundary*. The third level is made up by framework conditions that are predominately related to sociopolitical factors and/or the institutional quality of the country in question. An interesting historical parallel to high-income countries concerning the dynamic outer boundary can be found in Geels (2005). As part of his socio-technical landscape analysis of the transition from horse-drawn carriages to automobiles between 1860 and 1930, he refers to corruption as one of the driving and obstructing factors (dual influence) for the transition. As a developing country's sociopolitical status improves, e.g., moving towards increasing equality, the framework conditions that make up the *dynamic outer boundary* reduce their influence on the focal system, and eventually drop out as determinants for technological transitions. Once the dynamic outer boundary grows obsolete, the 2nd boundary becomes the outer boundary of the system. The framework conditions that make up the outer boundary in high-income countries and the 2nd boundary in developing countries, on the other hand, can be considered as more stable conditions, i.e., they will remain influential determinants of technological transitions to renewable energies for the foreseeable future.

6.5.1 Framework Conditions and Policy

While improving the conceptualization of framework conditions will assist a systematic analysis of their influence on technological transitions, the inclusion of framework conditions in the analysis of innovation systems also supports a wider discussion related to policy options.

If integral activities and their linkages delimit the system, policy interventions will be restricted to the actors (e.g., through policies such as tax credits or subsidies), or on the linkages directly involved in the technology (e.g., commercialization of R&D from universities or government research laboratories, involving actors in the private sector). Adding framework conditions to the analysis (i.e., delimiting the system with the outer boundaries) expands the alternatives for policies that can address both short-term (e.g., trade policy, regulation of business activities, etc.) and long-term (e.g., educated labor force or culture) barriers or drivers of the innovation system.

Even though certain framework conditions, such as unequal access to education, can only be fully addressed in the long-term, recognizing its role as a barrier to the system can open up the possibility for policy interventions that can circumvent the barrier in the short-term. For example, as was shown in the case of Kenya (Hansen, Pedersen, and Nygaard 2015), identifying the poorly educated labor force as an obstacle allowed them to temporarily circumvent the long-term framework condition by including targeted training into the donor supported RETs project. Developing strategies for tackling framework conditions in the short and long-term

is an important area for future research, which is enabled by the systems approach discussed in this chapter.

6.6 Concluding Remarks

Much of the emphasis in the technological innovation system approach literature has focused on the integral innovation activities or functions of the system. However, in order to achieve a full appreciation of the driving and obstructing factors of technological change, it is necessary to look beyond the system that is limited to actors, their activities and linkages. By taking a wider system of innovation approach and expanding the definition of what makes up a system, this chapter has focused on the determinants that are, in many cases, held to be exogenous to the system.

By combining a conceptual discussion with empirical data from previous studies, this chapter has highlighted framework conditions that exist in both developing and high-income countries. While framework conditions in general can be regarded as determinants for technological transition in countries of all income categories, the plurality of framework conditions in most developing countries suggests a particular relevance for their inclusion in technological transition analyses. The occurrence of framework conditions acting on the focal TIS in both developed and developing countries requires a re-thinking of the delimiting of the system. Moreover, this chapter has discussed how various types of framework conditions can influence the focal TIS through an interaction with existing institutions. In addition, this chapter has shown that by systematically incorporating framework conditions to complement the analysis of the functions or innovation activities, additional avenues for policies are made available that could enhance the success of future technological change.

The aim of this chapter has not been to provide a conclusive list of relevant framework conditions, nor is it practically possible given the context specificity of different countries. For example, the influence of incumbent actors was not included in the studies reviewed in this chapter. Instead, the aim has been to provide an initial overview of possible framework conditions and to stimulate future research on the topic. The evidence provided in the comparative literature analysis was not sufficient to infer any tangible evidence of differences of relevant framework conditions between developing countries, e.g., between low income and upper middle-income countries. This provides an avenue for further research, and over time, with additional empirical studies that include a framework analysis, framework conditions will be dropped or added in an organic manner, contributing to a more accurate delimiting of the system and supplemental information that can support policy development.

Chapter 7: Conclusions

This thesis has aimed to increase the knowledge of the factors that contribute towards sustainable development paths in developing countries. A particular focus and contribution of this thesis have been on improving the understanding of how developing countries can accelerate their transition towards RETs adoption, essential for enhancing energy security and reducing future emissions from anthropogenic Greenhouse Gases (GHG).

A holistic approach was taken to identify the determinants (positive-that contribute or negative-that hinder) of technological transitions (in particular renewable energy technologies - RETs) in developing countries. The research has also aimed to generate concrete policy suggestions. Through a combination of conceptual (Ch. 3 and 6) and empirical chapters (Ch. 4 and 5), a number of findings and lessons can be drawn. This chapter will revisit and highlight the key findings of this thesis, as well as discuss how they could have an impact on policy. The chapter concludes by reflecting on persisting knowledge gaps, while also providing ideas for how future research could build upon the findings presented in this thesis.

7.1 Integral Activities and Processes in Developing Countries

Chapter 3 conceptually addressed two major limitations of the Technological Innovation Systems (TIS) function approach and proposed an extended framework. Chapter 4 applied this extended framework to empirically identify obstructing and driving factors for wind energy adoption in Colombia. This section will review the findings from the empirical Chapter (4) and discuss how they can complement Chapter 3 by providing some initial insights into the validity of the conceptually motivated alterations to the framework. A full depiction of the findings from the function analysis will not be repeated here. The discussion is restricted to the empirical findings related to the proposed changes to the list of functions made in Chapter 3. To revisit the complete list of empirical findings from the function analysis please see Table 4.3 in Chapter 4.

Three out of the four suggestions proposed in Chapter 3 involved alterations to the baseline list of functions developed by Hekkert et al. (2007), in order for the framework to be better suited for developing countries. The proposed suggestions include adding *creating adaptive capacity*, *international resource mobilization*, and *informal legitimacy creation* functions to the baseline list. Moreover, contrary to previous studies (e.g., van Alphen, Hekkert, and van Sark 2008), Chapter 3 chose to keep the knowledge development function, to enable an analysis of changes in learning trends.

The findings in Chapter 4 showed positive learning trends in Colombia, with increased collaboration between actors engaged in research and small-scale innovation in wind and other RETs. The adaptive capacity of Colombia demonstrated a mixed picture, with high degree of qualified engineers in the urban centers (especially in Bogotá and Medellín), while significant human capacity constraints were revealed in remote rural areas. The organizational and institutional capacity in Colombia was described as a blocking mechanism to wind energy adoption because of e.g., high bureaucracy, slow decision-making and a reactive (informal) institutional culture. In regards to international resource mobilization, this function revealed availability of resources and an interest to invest in wind and other RETs in Colombia from international actors. However, the potential positive influence from this function is reduced by an insufficient guidance of the search (F4), i.e., lack of expectations set by the government, and a resistance to international financing due to fear of debt. Only scattered informal lobbying (legitimacy creation) for wind energy could be observed in Colombia from universities and smaller environmental groups, albeit with limited strength to influence other activities (functions) of the system, such as resources mobilization, guidance of the search or market formation. A more ample analysis in Chapter 3 of informal lobbying through social media was constrained by unavailability of historical social media data.

Based on the combined conceptual discussion in Chapter 3 and the empirical findings in Chapter 4, the following general lessons for the extended list of functions are provided. It is argued here that the *creating adaptive capacity* function should be included in the list of functions, as it allows mapping the ability of developing countries to receive a technology that was partly or entirely developed by foreign companies. Despite the common reliance on technologies initially developed by foreign companies (often in high-income countries), tracking knowledge development in the case of Colombia yielded interesting information about newly established research and small-scale innovations. It should be noted, however, that Colombia is an upper middle-income country with the ability to conduct high-quality domestic research. In low-income countries with very low capacity for R&D and innovation the relevance of mapping knowledge development trends may be reduced, and in this case, the argument can be made for dropping this function from the list.

Including the *international resource mobilization* function in Chapter 4, demonstrated that alternative resources for RETs investments are available. The international resource mobilization function can act as a complement that can reduce the blocking effect from a weak domestic resource mobilization function. At the same time, as was shown in the case of Colombia, without the support and interest from the government (guidance of the search), much of this potential positive effect from international resource mobilization could be lost. The conclusion based on Chapters 3 and 4 in this thesis is that the inclusion of the

international resource mobilization brings valuable information concerning the integral activities of the system and therefore should be included in the list of functions. Finally, while the addition of informal lobbying (legitimacy creation) was conceptually motivated in Chapter 3, Chapter 4 failed to show that it had any significant influence on the trajectory of wind energy adoption in Colombia. As was discussed in Chapter 3, it is fair to assume that with increased access to Internet and activity in social media in developing countries, combined with the pressing urgency of climate change and urban pollution, the influence from informal lobbying may increase in importance in coming years. However, it is also reasonable to concede to the notion that the influence from informal lobbying may remain limited in developing countries, and that this function, at this moment in time, may be of greater relevance in high-income countries.

The suggested additions to the TIS function approach that were conceptually justified in Chapter 3 and empirically tested in Chapter 4 are not meant to be a conclusive list of relevant activities or processes for technological systems in developing countries. However, the lessons and findings from these chapters should be seen as a complement to ongoing ambitions of improving the framework to analyze weaknesses and strengths of the systems under study. In accordance with Lundvall (1992), this process should be kept open and flexible to allow for dropping and adding of integral activities and processes (functions) to incrementally improve the delimitation of the system.

7.2 A Closer Look at ‘Exogenous’ Factors

The fourth suggestion in Chapter 3 and an overarching theme of this thesis is the recognition and proposed systematic inclusion of factors deemed exogenous to the TIS function approach, namely landscape factors or framework conditions. All chapters of this thesis addressed these framework conditions, however in different ways. While Chapters 3 and 4 drew much inspiration from the Multi-Level Perspective (MLP) approach to complement the TIS function analysis, Chapter 6, analyzed the role and influence of framework conditions from a wider Systems of Innovation (SI) approach. Chapter 5, on the other hand, was concerned with how a single framework conditions, environmental awareness, could be strengthened, by analyzing the effect from environmental education on environmental awareness and specific RETs awareness. The following sections will review the findings concerning landscape factors/framework conditions found in the chapters of this thesis.

7.2.1 Systematic Inclusion of Framework Conditions

Delimiting a system, or in other words differentiating it from the rest of the world, represents an essential aspect of any systems approach. Improving the accuracy of identifying the boundary of a technological system by its determinants (i.e., the

factors that allow the system to achieve its purpose) (Edquist 1997) has been addressed in several chapters of this thesis. Chapter 3 conceptually identified six landscape factors to be systematically analyzed as a complement to the TIS function approach, implicitly arguing that the functional analysis was inadequate to delimit the technical innovation system in developing countries. The six landscape factors that were conceptually motivated as determinants of the system were 1) Economic Growth; 2) Environmental Awareness; 3) Climate Change; 4) Armed Conflicts; 5) Corruption; and 6) Unequal Access to Quality Education. Chapter 4 included these landscape factors in the analysis to assess their influence on technological transition, specifically wind energy adoption, in Colombia.

Chapter 4 found both driving and obstructing influence from the landscape factors on the functions (integral actors and activities) of the system, with climate change demonstrating the strongest positive influence (i.e. contributing to adoption), and corruption and unequal access to quality education the strongest negative influence (i.e. obstructing adoption). More specifically, climate change related events, such as increased droughts (from more severe El Niño) and ensuing water shortages were found to positively influence the wind energy sector, as existing energy regimes (the hydropower and thermoelectric sector) faced deficiencies, resulting in increased pressure for the country to diversify its energy mix. Moreover, climate change was found to strongly contribute to the passing of several initiatives to expand wind energy and other RETs, such as the 'Low Carbon Development Strategy' and Renewable Energy (RE) Law.

Corruption, on the other hand, was found to block and/or slow down entrepreneurial activities (F1) and wind energy research projects (F2a), due to requests for informal payments at the local level. Unequal access to quality education largely explained the low access to skilled labor in remote rural areas of Colombia. Low access to skilled labor, in turn, reduced incentives for entrepreneurial activities (F1) in these areas. Paradoxically, many remote rural areas of Colombia have little or no access to electricity while having a high technical potential for wind energy, and could greatly benefit from electrification from Wind Energy and other RETs.

For the other landscape factors, i.e., economic growth, environmental awareness, and armed conflicts a lesser but not insignificant influence could be derived. For example, while the armed conflicts were expressed to negatively influence new investments, e.g., through higher interest rates, energy generating companies regarded it as a limited concern for new wind energy projects. The risks from the armed conflict could also be further reduced by thoroughly legitimizing the projects with the local community. For further details about landscape factors influence in Colombia, see Chapter 4.

Another step to improve the accuracy of the framework is to better understand the relevant determinants for technological transition in countries of different developmental status. Chapter 6 aimed to reduce the knowledge gap in this area by collating and comparing empirical findings of previous studies that had discussed the role of framework conditions (landscape factors) in developing (low, low-middle, upper-middle income) and developed countries (high-income).

In Chapter 6, 17 different framework conditions were identified and compared across 24 countries of different income categories. The plurality of framework conditions that influence technological change speaks to the difficulty of accurately delimiting the system. One of the main findings of Chapter 6 was that while several framework conditions overlapped across developed and developing countries, e.g., access to skilled labor, RET awareness and climate change, it appears that more framework conditions influence technological change in developing countries. This divergence is strongly tied to the developmental status of the country, where more elitists and lower quality institutions contribute to, for example, higher degrees of corruption and less distribution of wealth. Conclusions are made in Chapter 6 that an additional *dynamic outer boundary* should be included, which is made up by framework conditions such as income inequality, unequal access to quality education, corruption, etc. As the country in question develops (i.e., moves towards a more inclusive institutional set-up), these framework conditions gradually reduce their influence on technological change.

To conclude, the explicit and systematic inclusion on landscape factors/framework conditions in Chapter 3, 4 and 6 can provide an important step towards enhancing the understanding of the ‘wider context’ – outside the integral actors and activities (focal system) – and improving the comprehensiveness of the approach. As emphasized in Chapter 6, taking a wider systems approach, where all forms of determinants are treated as endogenous to the system, can be beneficial in more accurately delimiting the system and moving the systems approach towards a systems theory for analyzing technological change. While the focus in this thesis has been on the TIS, the findings presented also contribute to responding to critique made about the National Innovation System (NIS) approach when applied in a developing country context. For example, an explicit inclusion of framework conditions can help address the critique of Lundvall et al. (2002) that the NIS approach requires a broadening of its concepts to account for various instabilities (e.g., that of institutions) found in many developing countries.

7.2.2 Strengthening ‘Positive’ Framework Conditions

In Chapters 3, 4 and 6, this thesis has shown that framework conditions can have a positive or negative influence on technological transition. As was established in Chapter 3 environmental awareness represents one of these framework conditions that through a change in behavior in a population can positively influence

technological transition towards RETs and reduce the impact from the re-bound effect. Moreover, Chapters 3 and 6 demonstrated how a lack of RETs awareness in developing countries can act as a barrier for the new technology. For that reason, Chapter 5 of this thesis was dedicated to improving the understanding of how environmental awareness and specific awareness for RETs can be augmented.

In doing so, Chapter 5 analyzed the effect that environmental education can have on increasing environmental awareness and specific RETs awareness in 15-year olds. The chapter, which used OECD data from the Programme for International Student Assessment (PISA) in Colombia, found weak evidence that environmental education can strengthen environmental awareness, and an even lower effect on RETs awareness. While Chapter 5 did not find environmental education to be the silver bullet, the evidence suggests that strengthening environmental education in school curricula is a necessary but not sufficient condition for improving environmental awareness among the youth. For RETs awareness, other aspects such as socio-economic status, parents' background, and quality of educational resources or ownership (private or public) at the school level proved to be decisive explanatory factors.

Another interesting finding in Chapter 5 was that environmental optimism appeared to decrease with more environmental education. The idea that as students learn more about environmental concerns, they become less optimistic emphasizes the importance for parallel environmental initiatives outside the educational system. Increasing environmental awareness without providing alternatives for practicing 'greener' behavior, e.g., accessibility to recycling stations or affordable 'clean' energy could result in an attitude of indifference towards sustainability challenges. With these alternatives present, efforts in schools to promote individual responsibilities for environmental concerns could potentially reduce the decreasing optimism amongst youths.

7.3 Policy Implications

The topics and questions dealt with in thesis relate to sustainability issues of a time-sensitive nature. Mitigating an unsustainable human impact on the environment by expanding the adoption of RETs and by encouraging overall environmentally conscious decisions amongst the general public are issues that cannot be deferred to future generations. The urgency to address the challenges in this field of study stresses the importance for providing concrete policies that can help promote sustainable development. For that reason, this section is dedicated to discussing specific policy suggestions that can be derived from the chapters of this thesis.

The empirical lessons (Ch. 4) that were derived from analyzing the technological innovation system in Colombia revealed weaknesses within its functions and

provided policy suggestions to address these barriers to facilitate the expansion of wind energy in the country (see Table 4.3 in Chapter 4 for a complete list of barriers within the functions). The following section will discuss the policy implications from the landscape/framework condition analysis provided in this thesis, while also discussing their relations to certain policies for reducing weaknesses in the functions.

7.3.1 Long, Medium and Short-Term Policies for Innovation Systems

By expanding the analysis beyond the integral actors and activities of the system (focal system), a wider array of policy options that facilitate technological change becomes available. Firstly, the inclusion of the landscape/framework condition analysis in this thesis instigates a policy discussion from a long-term perspective, in order to take into consideration the slow changing framework conditions. For example, unequal access to quality education (Ch. 3) or culture (Ch. 6), relating the institutional structure of the country in question, requires years of incremental changes to be ‘fully’ addressed. Even though these structural framework conditions transcend terms of elected politicians, acknowledging and discussing long-term policy changes to tackle obstructing framework conditions deserves attention. Increasing the recognition amongst government organizations concerning the framework conditions discussed in this thesis and their role in creating a more innovation-prone environment is an important first step. The second step would be to devise policies to incrementally reduce obstructing factors and promote driving framework conditions into long-term national strategies, adapted to the unique country conditions.

While the long-term policies to address negative structural framework conditions are of great importance, devising policies for facilitating short or medium-term technological change are also necessary. The knowledge acquired from the framework conditions analysis can provide information about positive and negative conditions that can be temporarily circumvented through short-term policies. As was shown in Colombia, by thoroughly legitimizing new RETs with the local population, the risk of obstruction from armed groups is reduced. Therefore, building in local participation as central element during planning and implementation phase of new RETs projects, can reduce or remove risks from armed conflicts. Moreover, if awareness for RETs is expected to be low, building in information sessions with the community into the planned RETs project constitute a short-term policy that can help reduce potential negative effects from low RETs awareness. In the same fashion, obstruction from unequal access to quality education or low access to skilled labor could be partly circumvented by building specific skills training programs into the project, to train personnel before the implementation of the new technology. If short-term training policies are successful, they can be substituted by medium-term policies, moving towards a more permanent solution for improving RETs awareness and access to skilled

labor. Combining these types of short and/or medium-term policy fixes with incrementally resolving long-term structural obstructing framework conditions represent avenues for improving innovation policies as a result of the explicit and systematic framework condition analysis conducted in this thesis.

7.3.2 Remaining Challenges and Suggestions for Future Research

The findings in Chapter 3, 4 and 6 of this thesis suggests that the inclusion of a landscape/framework condition analysis to complement the examination of the integral actors and activities is beneficial for both enhancing comprehensiveness and to expand alternatives for policy. The extended TIS function approach developed in Chapter 3, and empirically tested in Chapter 4, should be seen first step to learning more about the links between the focal system and its wider context.

That said, ‘developing countries’ is a widely heterogeneous group and it cannot be assumed that all developing countries will benefit equally from the propositions provided in this thesis. The empirical analysis in this thesis has focused on Colombia, an upper-middle income developing country, which will most likely have different barriers, both within functions and framework conditions, to RETs adoption than a low-income developing country. Also, data availability can help determine the usefulness of the framework proposed in this thesis. Poor data availability to depict long-term trends in function and landscape factors or sectors in early formative stages is not uncommon in developing countries, and additional data collection and studies are required to complement existing results. For example, restricted data availability for several factors in Colombia resulted in an empirical analysis (Ch. 4) that was heavily reliant on the expert evaluations. Most likely, several lists, of both functions and framework conditions, will be required for countries of different development status, i.e., low-income, low middle-income, upper middle-income, and high-income countries.

Moreover, while the development of the extended TIS function approach, including the landscape/framework condition analysis, was developed with a developing country context in mind, there are several aspects, as shown in Chapter 6, which hold relevance in a high-income country context as well. Differences between high-income and developing countries also represent an area in need of additional research. For example, in what way does global governance, through international organizations, such as the World Bank, International Monetary Fund (IMF) or World Trade Organization (WTO) influence developing countries as compared to high-income countries in their path towards RETs adoption; this is a question that was not explicitly addressed in this thesis. This represents one interesting avenue for future work, which will require more empirical studies that continue developing the understanding of the drivers and obstacles for

technological transitions in countries of different development stages and income levels.

The long and short-term policies enabled by treating framework conditions as endogenous to the system (Ch. 6) are an interesting avenue for future research, which was not addressed to a great extent in this thesis. Just as learning about and developing policies for reducing or removing blocking mechanisms for technological transition is an important area for research, better understanding how positive framework conditions can be strengthened (Ch. 5) also deserves further attention. The empirical knowledge about environmental education needs to be complemented with more studies from developing countries to fully access the potential of the education sector to strengthen environmental awareness. Moreover, beyond the role of the education sector, increasing the knowledge of strategies to reinforce awareness building of society in general, and identifying the appropriate incentive structures is required to transform initial awareness into changed behavior.

Finally, continuing with a flexible approach to the list of functions is preferred, in order to incrementally improve the understanding of integral innovation activities that make up the focal TIS. However, focusing future research on technical and economic aspects of energy transition alone is likely to fall short of its goals. Giving more attention to framework conditions such as culture or environmental awareness can help reduce resistance to the technology and improve the environment for innovation. The field of psychology can complement existing transition research by bringing a greater understanding of the behavior of the population in which the technology aims to be diffused. In order for future research to be successful in addressing the many challenges facing socio-technical transitions as well broader sustainability goals, a special prominence should therefore be placed on greater collaboration between different related fields.

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Appendix I: Interview Guide, Forms and List of Key Actors

Appendix I provides additional information concerning the data from the structured and semi-structured interviews conducted in Bogota, Colombia between April 21-June 18, 2014. The objective with the fieldwork was to conduct structured and semi-structured interviews with key actors and experts in the field of Wind Energy in Colombia in order to determine the fulfillment of each of the TIS functions and perceived importance of Landscape Factors in terms of their influence on the formation of wind energy projects and other RETs. Key stakeholders and experts in the field involve senior representatives from industry, research institutions, government, non-governmental organizations and environmental groups in order to determine to what extent each of the functions has been fulfilled. Appendix I presents a detailed description of the method for the collecting this data, including a full list of key actors involved in the study.

Method for Selecting Key Actors

Before conducting the fieldwork, a preliminary review of potential key actors was conducted, which provided the baseline for sampling. Based on this preliminary identification of key actors in Colombia, and to guarantee wide representation of key actors (experts) that actively work within the field of wind energy and other RETs in Colombia, a maximum variation sampling was applied before the beginning the fieldwork. During the fieldwork, snowball sampling was used to reach and set up additional interviews with experts in Colombia.

Full List of Key Actors Interviewed

Type of Actor	Name of Organization	Participated in Structured Interviews	Participated in Structured Interviews
Energy Generating Companies	ISAGEN	Yes	Yes
	ISAGEN	No	Yes
	ISAGEN	No	Yes
	ISAGEN	No	Yes
	EMGESA	Yes	Yes
	ENEL Green Power	No	Yes
Research Institutions	Universidad de Los Andes	Yes	Yes
	Universidad de la Salle	Yes	Yes
	Universidad de la Salle	Yes	Yes
	Universidad de la Salle	Yes	Yes
Government Agencies	DNP – Subdivision Medio Ambiente (Environment	Yes	Yes

	Sub- Division)		
	DNP – Subdivision Minas y Energía (Mines and Energy Division)	Yes	Yes
	UPME	Yes	Yes
	UPME	Yes	Yes
	UPME	Yes	Yes
International Actors	Inter-American Development Bank	Yes	Yes
Total Number of Interviews			16
Percentages Participating in Structured and Semi-Structured Interviews		75%	100%

Note 1: For explanations of the acronyms see *List of Acronyms* at the beginning of the thesis.

Note 2: Interviews with ISAGEN were conducted over Skype. All other interviews were conducted *in-situ*.

Structured Interview Form (Translated)

Before the semi-structured interviews, a document in was shared in Spanish (see box 1) by email to each interviewee before the meeting, which included a brief introduction about the study (its purpose, description of the (extended) TIS framework and role of functions and landscape factors developed in Chapter 2).

As part of the document, participants were asked to rate their level of satisfaction with each of the functions (fulfillment) and indicate their view of the importance of the landscape factors for the transition towards wind energy and other RETs in Colombia, based on a 5-point rating scale (Likert scale), including the option of N/A in the following manner:

Rating Functions	Rating – Landscape Factors
1 point = very weak	1 point = Not important
2 points = weak	2 points = Of little importance
3 points = sufficient	3 points = Important
4 points = good	4 points = Very important
5 points = very good	5 points = Extremely important
N/A = Not Applicable	N/A = Not Applicable

The result of the expert evaluation was then compounded and an average between 1 and 5 of the result was presented as part of Chapter 3. The manner of how the data would be used and displayed in the study was explained to the participants before the start of the meeting.

Box 1. Actual Structured Interview Form Sent Out Before Interviews (*in Spanish*)

Objetivo y Descripción del Estudio

El objetivo del estudio es investigar las barreras para la adopción de la Energía Eólica en Colombia. Para el estudio planeo usar una combinación de dos marcos analíticos: El Enfoque de Funciones del Sistema de Innovación Tecnológica (Technological Innovation System Function Approach: TIS) (Hekkert et al., 2007) y la Perspectiva Multinivel (Multi-level Perspective (MLP))¹.

Estos marcos analíticos usan la terminología de “Funciones” (Functions) y Factor Externo (Landscape Factor). La palabra “Funciones” se refiere a varias partes del sistema de innovación. Para este estudio el sistema de innovación se refiere a la energía eólica. La palabra “Factor Externo” se refiere a los factores considerados externos a los aspectos integrales del sistema de innovación.

La primera parte del estudio consiste en entrevistas estructuradas. Las entrevistas estructuradas sirven como una parte importante para entender las barreras y para desarrollar estrategias para poder acelerar la adopción de Energía Eólica en Colombia u otros países con características similares.

Para la parte estructurada de la entrevista, por favor indique su nivel de satisfacción de cada función y la importancia de cada factor externo de acuerdo a su perspectiva en cuanto al avance y desarrollo de la energía eólica en Colombia, así como las barreras que pueden estar impidiendo una mayor adopción de la misma. Para identificar su nivel de satisfacción con cada función y factor externo favor clasifique del 1 al 5 de la siguiente manera:

Clasificado – Funciones	Clasificado – Factores Externos
1 punto = muy mal	1 punto = No es importante
2 puntos = mal	2 puntos = Poco importante
3 puntos = aceptable	3 puntos = Importante
4 puntos = bien	4 puntos = Muy importante
5 puntos = muy bien	5 puntos = Extrema importancia
N/A = No es Aplicable	N/A = No es Aplicable

Funciones		Descripción	Puntos
F1	Actividades de emprendimiento	Actividades de emprendimiento en el sector de Energía Eólica	
F2a	Creación de Conocimiento	Investigación en Energía Eólica	
F2b	Capacidad de adaptación	Capacidad humana (capacidad y conocimiento técnico), organizacional, e institucional	
F3	Diseminación de conocimiento	Diseminación de conocimiento de Energía Eólica, por ejemplo en talleres o conferencias.	
F4	Dirección de la búsqueda	Metas por parte del gobierno o actores privados	
F5	Formación de mercado	Regímenes fiscales (subsidios, incentivos económicos), marco regulatorio propicio	
F6a	Recursos movilizados por el gobierno	Recursos del gobierno (ej. subsidio, inversiones) en energía eólica	
F6b	Recursos movilizados del extranjero	Ayuda (donaciones) y préstamos internacionales hacia energía eólica.	
F7a	Creación de legitimidad de grupos formales	Cabildeo/actividades para ejercer presión (<u>lobbying</u>) por parte de grupos formales y establecidos (<u>compañías y organizaciones</u>)	
F7b	Creación de legitimidad de grupos informales	Actividades para ejercer presión (<u>lobbying</u>) de manera informal, ej. opinión pública y aceptación en los medios sociales	
Factores Externos		Descripción	Puntos
FE1	Crecimiento Económico	Por favor indique su opinión sobre la importancia e impacto de cada factor externo en el desarrollo y difusión de la Energía Eólica en Colombia.	
FE2	Conciencia medio ambiental por parte de la sociedad civil		
FE3	Cambio Climático		
FE4	Conflicto armado		
FE5	Corrupción		
FE6	Desigualdad en el acceso a la educación		

¹ Estos marcos se basan principalmente en el trabajo de Hekkert et al., 2007 y Geels, 2002, respectivamente.

Semi-Structured Interviews

In addition to the Likert scale, the interviewees were given the opportunity to provide their perspectives on what are the main impeding factors for an enhanced system performance along with suggesting strategies for improvement. For reliability and comparability purposes, a set of interview questions for all the functions and landscape factors was prepared on beforehand and used for all interviews.

Ethics – Disclosing of Personal Details

The interviews were recorded by audio, after the interviewees gave consent. 100% of the interviews conducted gave their consent for audio recording. It was agreed at the start of the interviews with all participants that their individual names would not be included in the final depiction of the data, only the name of their organization.

Average Interview Length

The planned averaged total length of each interview was 1 hour. Most of the interviews followed the planed average length, with some exceptions going slightly over time.

Semi-structured Interview Questions (Guideline)

	Questions (In Spanish):		Questions (In English):	
Function 1: <i>Actividades de Emprendimiento</i> (Entrepreneurial Activity)	1.1	¿En su opinión, cuál puede ser la estrategia más importante para aumentar los proyectos eólicos en Colombia?	1.1	In your opinion, what would be the most important strategy to increase the number of new Wind Energy projects?
Function 2a: <i>Creación de Conocimiento</i> (Knowledge Creation)	2.1a	¿Qué aspecto de creación de conocimiento (investigación) sobre energía eólica necesita la mayo atención?	2.1a	What aspect of knowledge creation concerning WE is in most need of improvement?
Function 2b: <i>Capacidad Adaptativa</i> (Adaptive Capacity)	2.1b	¿Cómo describiría usted la capacidad adaptativa de Colombia para la adopción de energía eólica? La capacidad adaptativa se refiere a la capacidad humana (capacidad técnica), organizacional, e institucional.	2.1b	How would you describe the adaptive capacity of Colombia, that is, the human (technical capacity), organizational, and institutional capacity for adopting WE?
	2.2b	¿Existe alguna discrepancia entre los conocimientos	2.2b	Is there a mismatch between the supply of

		técnicos referentes a la energía eólica suministrados por las universidades y la demanda de la industria? ¿y existe alguna discrepancia entre la necesidad de profesionales especializados y la cantidad de profesionales capacitados disponibles?		technical knowledge of WE produced by Universities and the demand by the energy generating companies? (The right type of skills and the adequate amount of skilled labor)
Function 3: <i>Difusión de Conocimiento</i> (Knowledge Diffusion)	3.1.	¿En su opinión, cuál es la manera más importante para difundir el conocimiento sobre la energía eólica que promueva su adopción?	3.1.	In your opinion, what is the most important manner in which knowledge concerning WE can be diffused to promote adoption?
	3.2.	¿Qué tipo y cantidad de colaboración existe entre actores nacionales e internacionales sobre la energía eólica?	3.2.	What amount and type of national and international collaborating exist between actors within the WE Innovation System?
	3.3.	¿Qué tipo de conocimiento es compartido entre estos actores o bajo estas alianzas?	3.3.	The kind of knowledge that is shared within these existing partnerships?
	3.4.	¿Qué tan a menudo son organizados eventos oficiales donde se comparte información?	3.4.	What type and how often are official gatherings organized, where information is exchanged?
Function 4: <i>Orientación de la Búsqueda</i> (Guidance of the Search)	4.1.	¿En su opinión, qué le gustaría ver en cuanto a orientación por parte del gobierno? Metas o regulaciones.	4.1.	In your opinion, what would you like to see in terms of guidance from the government?
	4.2.	¿Qué metas o regulaciones están siendo impuestas por el gobierno?	4.2.	What specific targets or regulations are being set by the government?
	4.3.	¿Qué tipo de visiones y expectativas existen frente a la energía eólica?	4.3.	What type of visions and expectations exist about Wind Energy?
Function 5: <i>Creación del Mercado</i> (Market Creation)	5.1.	¿Cuáles son los principales obstáculos para la creación y/o fortalecimiento del mercado de energías eólicas? ¿Impuestos, estándares?	5.1.	What obstacles to market creation and/or strengthening are most pressing?
	5.2.	¿Cuál es el estado del mercado de energías eólicas y su	5.2.	What phase is the market in and what is its (domestic &

		potencial doméstico y externo?		export) potential?
	5.3.	¿Qué tipo de incertidumbres enfrentan los potenciales desarrolladores de proyectos?	5.3.	What are some uncertainties faced by potential project developers?
Function 6a: <i>Recursos movilizados por el gobierno</i> (Resource Mobilization (government))	6.1a	¿Cuál es el recurso económico con mayor escasez necesario para la energía eólica?	6.1a	What is the most pressing resource scarcity for WE?
	6.2a	¿Cuál es la disponibilidad de capital financiero (capital semilla, capital de riesgo, fondos del gobierno para ID&D)?	6.2a	How is the availability of financial capital (seed and venture capital, government funds for RD&D)?
Function 6b: <i>Movilización de recursos internacionales</i> (Resource mobilization - international funding)	6.1b	¿Qué importancia juega la financiación internacional en la adopción de EE en Colombia? ¿Es suficiente?	6.1b	What role does international funding play in adoption of WE in Colombia? Is it sufficient?
Function 7a. <i>Creación de legitimidad/ Lobby formal</i> (Creation of Legitimacy/ Advocacy coalition -formal lobbying)	7.1a	¿Qué tan activos son los grupos de lobby a favor de la energía eólica (tamaño y fuerza)? ¿Han crecido en la última década?	7.1a	How active are lobby groups for WE. Their size and strength? Have they been growing in the past decade?
	7.2a	¿Cómo ha sido el cambio en la legitimidad para invertir en la tecnología?	7.2a	How has the legitimacy to make investments in the technology changed?
	7.3a	¿Cuáles son los principales actores, a favor y en contra, del desarrollo y adopción de la energía?	7.3a	What are the main arguments of actors pro or against the deployment the technology?
Function 7b: <i>Creación de legitimidad/Lobb y informal</i> (Creation of Legitimacy/ Advocacy coalition - informal lobbying)	7.1b	¿Ha experimentado cambios en las actividades en medios sociales, donde temas como sostenibilidad, energía renovable, y energía eólica se hayan discutido?	7.1b	Have you experienced a change in the activities in social media, where sustainability, RET and wind energy has been discussed, and in what manner, positive or negative?
	7.2b	¿En su opinión, cuál es la actitud del público frente a la tecnología y como es presentada la tecnología en los	7.2b	In your opinion, how is the Public opinion towards the technology and how is the technology

		medios?		depicted in the media?
Factor Externo 1: <i>Crecimiento Económico</i> (Landscape Factor 1: Economic Growth)	1.1.	¿En su opinión, la situación económica en Colombia está contribuyendo o impidiendo la difusión de energía eólica?	1.1.	In your opinion, is the economic situation in Colombia benefitting or impeding WE diffusion in Colombia?
	1.2.	¿Ha visto un cambio de recursos hacia la EE que esté siguiendo el nivel de crecimiento económico?	1.2.	Have you seen a change in resources towards WE that followed the level of economic growth?
	1.3.	¿Cómo ha afectado la crisis económica los recursos y legitimidad de EE en Colombia?	1.3.	How has the economic crisis influenced resources and legitimacy towards increased WE in Colombia?
Landscape Factor 2: Consciencia ambiental (Environmental Awareness)	2.1.	¿Qué influencia tiene la concientización medio ambiental en la difusión de la EE y Energía Renovable (ER)?	2.1.	What role does environmental awareness play for WE and RET diffusion?
	2.2.	¿Ha notado cambios en la concientización/conocimiento de la EE y las ER en Colombia?	2.2.	Do you see a change in awareness for WE and RET in general in Colombia?
Landscape Factor 3: <i>Cambio Climático</i> (Climate Change)	3.1.	¿Cuáles han sido los impactos del cambio climático en Colombia? o ¿de qué manera ha influido el cambio climático al país? ¿Cuáles son los impactos más urgentes?	3.1.	Has Colombia been influenced by Climate Change (CC)? In what way? What is the most pressing aspect?
	3.2.	¿Cómo ha afectado el cambio climático la movilización de recursos para la EE y las ER? ¿De qué manera han influido los impactos relacionados al cambio climático influido la concientización sobre los riesgos de la inacción? y ¿de	3.2.	Has Climate Change related events influenced awareness concerning the risks of inaction and has it helped legitimize WE? Has the

		qué manera ha contribuido la concientización sobre el cambio climático en la legitimización de la EE?		mobilization of resources towards WE and other RET been influenced by CC?
Landscape Factor 4: <i>Conflicto Armado</i> (Armed Conflict)	4.1.	¿En su opinión, de qué manera está afectando el conflicto armado en Colombia las inversiones en EE?	4.1.	In your opinion, does the armed conflict in Colombia affect investments towards WE?
	4.2.	¿Influye el costo del conflicto en la movilización de recursos hacia la EE?	4.2.	Does the cost of the conflict influence resource mobilization towards WE?
	4.3.	¿Contribuye el conflicto a niveles de inseguridad que puedan obstaculizar nuevos desarrollos de EE y otras formas de ER?	4.3.	Does the conflict contribute to levels of insecurity that have obstructed potential new developments of WE and other forms of renewable energy?
Landscape Factor 5: <i>Corrupción</i> (Corruption)	5.1.	¿Influye la corrupción la movilización de recursos para la EE?	5.1.	Does corruption influence resource mobilization towards WE?
	5.2.	¿Ha influido la corrupción en la interrupción de emprendimientos eólicos?	5.2.	Has corruption contributed to entrepreneurial activity being canceled?
Landscape Factor 6: <i>Desigualdad en el acceso a educación</i> (Inequality: Unequal Access to Quality Education)	6.1.	¿Es el acceso a la educación superior un tema problemático en Colombia?	6.1.	Is access to higher education an issue in Colombia?
	6.2.	¿Hace falta mano de obra calificada en Colombia hasta el punto que pueda obstaculizar el desarrollo de la EE? Y ¿hasta qué punto está el acceso desigual a la educación superior contribuyendo a la discrepancia entre disponibilidad y demanda de personal calificado?	6.2.	Is there a lack of skilled labor in Colombia that might hamper the development of WE? And to what extent is unequal access to higher education contributing to this discrepancy?

Transcribing

The interviews were manually transcribed using *Express Scribe*, as the automatic dictation did not exist for Spanish.

Analysis of Data

The transcribed text was organized and analyzed manually using Microsoft Excel. Trends in the answers from different actors were identified and displayed in Chapter 4 in the text. Direct quotes were translated to English and also displayed in the analysis section of Chapter 4.

Appendix II: Scales Constructed by PISA (OECD 2009)

Name of Scale	Label	Main Question	Response Alternatives
Environmental Awareness	Envaware	How informed are you about the following environmental issues?	1 I have never heard of this 2 I have heard about this but I would not be able to explain what it is really about 3 I know something about this and could explain the general issue 4 I am familiar with this and I would be able to explain this well
		Items a) The increase in greenhouse gases in the atmosphere b) Use of genetically modified organisms (GMO) c) Acid rain d) Nuclear waste e) The consequences of clearing forests for other land use	
Responsibility for Sustainable Development	Respdev	How much do you agree with the statements below?	1 Strongly agree 2 Agree 3 Disagree 4 Strongly disagree
		Items a) It is important to carry out regular checks on the emissions from cars as a condition of their use b) It disturbs me when energy is wasted through the unnecessary use of electrical appliances c) I am in favour of having laws that regulate factory emissions even if this would increase the price of products d) To reduce waste, the use of plastic packaging should be kept to a minimum e) Industries should be required to prove that they safely dispose of dangerous waste materials f) I am in favour of having laws that protect the habitats of endangered species g) Electricity should be produced from renewable	

		sources as much as possible, even if this increases the cost		
Environmental Optimism	Envopt	Do you think problems associated with the environmental issues below will improve or get worse over the next 20 years?	1 2 3	Improve Stay about the same Get worse
		Items		
		a) Air pollution		
		b) Energy shortages		
		c) Extinction of plants and animals		
		d) Clearing of forests for other land use		
		e) Water shortages		
		f) Nuclear waste		
Perception of Environmental Issues	Envperc	Do you see the environmental issues below as a serious concern for yourself and/or others?	1 2 3 4	This is a serious concern for me personally as well as others This is a serious concern for other people in my country but not me personally This is a serious concern only for people in other countries This is not a serious concern to anyone
		Items		
		a) Air pollution		
		b) Energy shortages		
		c) Extinction of plants and animals		
		d) Clearing of forests for other land use		
		e) Water shortages		
		f) Nuclear waste		
Environmental Education	Envedu	Does your school organize any of the following activities to provide opportunities to students in <national modal grade for 15-year-olds> to learn about environmental topics?	1 2	Yes No
		Items		
		a) Outdoor education		
		b) Trips to museums		
		c) Trips to science and/or technology centres		

Name of Scale	Label	Main Question	Response Alternatives
		d) Extracurricular environmental projects (including research) e) Lectures and/or seminars (e.g. guest speakers)	
Enjoyment of science	Joyscie	How much do you agree with the statements below? Items a) I generally have fun when I am learning broad science topics b) I like reading about broad science c) I am happy doing broad science problems d) I enjoy acquiring new knowledge in broad science e) I am interested in learning about broad science	1 Strongly agree 2 Agree 3 Disagree 4 Strongly disagree
Constructivist Science Teaching		When learning science topics at school, how often do the following activities occur? Items	1 In all lessons 2 In most lessons 3 In some lessons 4 Never or hardly ever
Models or applications	Scapply	a) The teacher explains how a school science idea can be applied to a number of different phenomena (e.g. the movement of objects, substances with similar properties) b) The teacher uses science to help students understand the world outside school c) The teacher clearly explains the relevance of broad science concepts to our lives d) The teacher uses examples of technological application to show how school science is relevant to society	
Interaction	Scintact	a) Students are given opportunities to explain their ideas b) The lessons involve students' opinions about the topics c) There is a class debate or	

		discussion	
		d) The students have discussions about the topics	
Investigations	Scinvest	a) Students are allowed to design their own experiments	
		c) Students are asked to do an investigation to test out their own ideas	
Hands-on Activities	Schands	a) Students spend time in the laboratory doing practical experiments	
		b) Students are required to design how a school science question could be investigated in the laboratory	
		c) Students are asked to draw conclusions from an experiment they have conducted	
		d) Students do experiments by following the instructions of the teacher	
Science Activities	Scieact	How often do you do these things?	1 Very often
			2 Regularly
		Items	3 Sometimes
		a) Watch TV programmes about broad science	4 Never or hardly ever
		b) Borrow or buy books on broad science	
		c) Visit web sites about broad science topics	
		d) Listen to radio programmes about advances in broad science	
		e) Read science magazines or broad science articles in newspapers	
		f) Attend a science club	
Parents' view on general value of science	Pqgensci	The following question asks about your views towards science. How much do you agree with the following statements?	1 Strongly agree
			2 Agree
			3 Disagree
			4 Strongly disagree

Name of Scale	Label	Main Question	Response Alternatives
Items			
a) Advances in broad science and technology usually improve people's living conditions			
b) Broad science is important for helping us to understand the natural world			
c) Advances in broad science and technology usually help improve the economy			
d) Broad science is valuable to society			
e) Advances in broad science and technology usually bring social benefit			
Parent's view on personal value of science	Pqpersci	The following question asks about your views towards science. How much do you agree with the following statements?	1 Strongly agree 2 Agree 3 Disagree 4 Strongly disagree
Items			
a) Some concepts in broad science help me to see how I relate to other people			
b) There are many opportunities for me to use broad science in my everyday life			
c) Broad science is very relevant to me			
d) I find that broad science helps me to understand the things around me			
Parents' science activities at age 10	Pqsciact	Thinking back to when your child was about 10 years old, how often would your child have done these things?	1 Very often 2 Regularly 3 Sometimes 4 Never or hardly ever
Items			
a) Watched TV programmes about science			
b) Read books on scientific discoveries			
c) Watched, read or listened to science fiction			

		d) Visited web sites about science topics	
		e) Attended a science club	
Quality of education resources	Scmatedu	Is your school's capacity to provide instruction hindered by any of the following?	1 Not at all 2 Very little 3 To some extent 4 A lot
		Items	
		a) Shortage or inadequacy of science laboratory equipment	
		b) Shortage or inadequacy of instructional materials (e.g. textbooks)	
		c) Shortage or inadequacy of computers for instruction	
		d) Lack or inadequacy of internet connectivity	
		e) Shortage or inadequacy of computer software for instruction	
		f) Shortage or inadequacy of library materials	
		g) Shortage or inadequacy of audio- visual resources	
Teacher shortage (Not inverter for scaling)	Tcshort	Is your school's capacity to provide instruction hindered by any of the following?	1 Not at all 2 Very little 3 To some extent 4 A lot
		a) A lack of qualified science teachers	
		b) A lack of qualified mathematics teachers	
		c) A lack of qualified test language teachers	
		d) A lack of qualified teachers of other subjects	

Valorisation Addendum

In accordance with article 23.5 of the “Regulation governing the attainment of doctoral degrees at Maastricht University” decreed by resolution of the Board of Deans, dated 3 July 2013, an addendum must be added about valorization.

Relevance

An increasing world population combined with a rapidly rising material and per capita energy consumption is creating an ecological deficit, where roughly 1.5 planets are required to provide the necessary resources (Global Footprint Network 2015). The overarching motivation behind conducting the research in this thesis comes from the urgent need to reduce natural resource consumption to levels that can support human life and development in the future.

Reducing fossil fuel-based energy consumption that is contributing to climate change represents one important strategy to reduce its impacts and the ecological deficit. The importance of this strategy has been emphasized in goal 7 of the United Nation’s *Sustainable Development Goals (SDGs)*, which aims to: *Ensure access to affordable, reliable, sustainable and modern energy for all*. In addition, the Climate Change Paris Agreement, signed in 2015 and ratified by 169 out of 197 parties, has as an ambition to combat climate change. Expanding access to and the use of renewable energy technologies is considered one significant component in achieving that goal.

Meeting the goals of reduced emissions requires a rapid and successful expansion of a wide range of mitigation alternatives. This thesis has focused on increasing the knowledge regarding the driving and obstructing mechanisms for expanding renewable energy technologies (RETs), with a special focus on developing countries. The thesis does this through a combination of conceptual and empirical chapters, including a study on wind energy adoption in Colombia. The focus on developing countries is particularly relevant as projections to 2040 show that energy use is expected to grow substantially, predominately in non-OECD countries (>85% of the increase), as a result of population increase, economic growth and higher standards of living (EIA 2013). Global projections estimate that global emissions in developing or emerging countries will exceed that of the developed world in the next decades (EIA 2013). At the same time, approximately 1.2 billion people are without access to any form of electricity and without successful policy interventions, 1 billion people are still expected to be without electricity in 2030 (IEA 2015). Worst off is Sub-Saharan Africa, with data from 2014 demonstrating that only 35% of the population has access to electricity, with as little as 19% in rural areas (IEA 2016b). Beyond the positive environmental

implications, given the low operation and maintenance costs, RETs could also be considered a principal instrument in alleviating energy poverty in developing countries (Bhide and Monroy 2011).

Due to the importance that an increased access to clean and affordable energy (SDG 7) can have on positively affecting other developmental issues, the relevance of the research in this thesis can also be found through a direct or indirect support of several other SDGs. For example, a supply of reliable and clean energy would contribute to the infrastructure that enables innovation and industry development (SDG 9) to occur. Consequentially, by facilitating the formation of new firms, work opportunities and reduced poverty (SDG 1) will followed.

Another example for how the research conducted in this thesis connects to other SDGs is its potential to reduce energy poverty in rural remote areas where the incentive to extend the national electricity grid is limited. As both schools and health clinics are dependent on a reliable source of electricity to provide quality education (SDG 4) and good health care (SDG 3), expanding RETs in these areas can play an important role in reaching these SDGs. Moreover, as has been discussed in this thesis, the expansion of RETs adoption represents one of the essential mitigation strategies for reducing green house gas (GHG) emissions (Climate Action-SDG 13).

In reducing the risk from conflict generated by climate change migration and energy insecurity, the relevance of the research conducted in this thesis can also be found in SDG 16 (peace, justice and strong institutions). In addition, in order to achieve sustainable cities and communities (SDG 11), an increased supply of electricity from RETs is pivotal to transition from a fossil fuel based transport sector to electricity-based vehicles, without increasing CO₂ equivalent emissions and exacerbating climate change (SDG 13).

Innovation

This thesis proposes an extended technological innovation system function approach that can be considered innovative when compared with the earlier approach. Through the extended approach, this research has provided additional pathways to observe and understand the processes behind transitioning to renewable energy technologies. The thesis proposes a systematic and explicit inclusion of framework conditions, which would benefit future transition studies, both for high-income and developing countries.

Moreover, the evidence presented in this thesis suggests that the prominence and prevalence of relevant framework conditions is higher in developing countries, thus bringing attention to the importance of delimiting the system boundaries to include not only the technological innovation under study but also wider

framework conditions. In other words, the thesis suggests that a number of conditions that may exercise positive (contributing) or negative (hindering) effects on technological transitions, in this case RETs, should be regarded as endogenous rather than exogenous to the system. For example, in the extended TIS function analysis conducted in Colombia, which complemented the TIS function approach by systematically and explicitly analyzing the influence of framework conditions (landscape factors), revealed several interesting findings were revealed.

The thesis found both driving and obstructing influences from the landscape factors on the functions (integral actors and activities) of the system, with climate change demonstrating the strongest positive influence (i.e. contributing to adoption), and corruption and unequal access to quality education the strongest negative influence (i.e. obstructing adoption). More specifically, climate change related events, such as increased droughts (from a more severe El Niño) and ensuing water shortages were found to positively influence the wind energy sector, as existing energy regimes (the hydropower and thermoelectric sectors) faced deficiencies, resulting in increased pressure for the country to diversify its energy mix. Moreover, climate change was found to strongly contribute to the passing of several initiatives to expand wind energy and other RETs, such as the 'Low Carbon Development Strategy' and Renewable Energy (RE) Law.

Corruption, on the other hand, was found to block and/or slow down entrepreneurial activities and wind energy research projects, due to requests for informal payments at the local level. Unequal access to quality education largely explained the low access to skilled labor in remote rural areas of Colombia. Low access to skilled labor, in turn, reduced incentives for entrepreneurial activities in these areas. Paradoxically, many remote rural areas of Colombia have little or no access to electricity while having a high technical potential for wind energy, and could greatly benefit from electrification from Wind Energy and other RETs.

For the other landscape factors, i.e., economic growth, environmental awareness, and armed conflicts, a lesser but not insignificant influence could be identified. For example, while the armed conflicts led to a negative influence on new investments, e.g., through higher interest rates, energy generating companies regarded armed conflicts as a limited concern for new wind energy projects. Seeking approval and support for planned projects from the local community could also further reduce the risks from the armed conflict. For further details about the influence of landscape factors influence in Colombia, see Chapter 4.

Finally, the extended approach presented in this thesis expands the options of policies that are necessary to circumvent the barriers that are hampering the introduction and/or acceleration of clean energy alternatives, which can be considered an innovation compared with previous approaches used to analyze technological transitions.

By also discussing the innovation system approach from a broader perspective, the thesis has highlighted links between the TIS function approach and other approaches to measure innovation activities. One such link can be made between the *innovation activities* raised as part of the Oslo Manual (third edition) and the TIS functions, which could stimulate further research in the academic community to develop a more coherent approach to measure innovation in systems where RETs are present.

Target Groups

The research conducted in this thesis is relevant for both the academic community and policy makers and analysts in national governments or international organizations. For the national governments or international organizations working on projects to expand the use of renewable energy in developing countries, the result of the conceptual and empirical chapters in this thesis could inform decision-making and enhance policy design. For the academic community, the material presented could contribute to both the existing knowledge base for transition studies in developing and high-income countries, while adding to the ongoing effort to enhance the theoretical understanding of a technological system, its determinants and boundaries.

Dissemination

The results of this thesis (Chapters 3-6) will be disseminated to both academics and policy makers in Colombia and elsewhere that are engaged with energy policies and renewable energy adoption. Prior to the completion of this thesis, the key findings of Chapter 3 and 4 have been disseminated in international conferences, namely at the 14th *Globelics International Conference* in Bandung (Indonesia) and the 6th *International Sustainability Transitions (IST-6) Conference* in Brighton (UK), respectively.

In addition to being presented at international conferences, findings from Ch. 3 and 4 have been published as working papers and in peer-reviewed journals. Chapter 3, titled: *Technological Innovation System and the Wider Context: A framework for developing countries* has been published as a working paper at the UNU-MERIT working paper series in 2016 (Edsand 2016). Chapter 4, titled: *Identifying Barriers to Wind Energy Diffusion in Colombia: A Function Analysis of the Technological Innovation System and the Wider Context*, was published in 2017 in the journal *Technology in Society* (Edsand 2017). Chapter 5 (*The Impact of Environmental Education on Environmental and Renewable Energy Technology Awareness: Empirical Evidence from Colombia*) has been submitted to a peer-reviewed journal and is currently under review. In the time following the PhD, Chapter 3 and Chapter 6 (*Framework Conditions of Technological Transition: Re-thinking the*

Boundary for a Technological Innovation System) of this thesis will be submitted for dissemination through suitable peer-reviewed journals.

About the Author

Hans-Erik (Hasse) Edsand joined the PhD program at UNU-MERIT/Maastricht Graduate School of Governance in 2012. He holds an MSc in Development Studies from the School of Oriental and African Studies (SOAS), University of London.

Prior to joining the PhD program at UNU-MERIT, Hasse worked with policy research and implementation of education, health and social protection projects in developing countries at the World Bank and the Inter-American Development Bank.

Other activities at UNU-MERIT during the PhD include the co-development and coordination of a short educational program (Evidence-Based Research Policy Research Methods (EPRM)), along with in-class teaching and online tutoring of qualitative methods.

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