UN-LOCKING LOCK-IN:
TRANSITION TO TRANSITION COSTS

A NEW THEORY ON TRANSITION COSTS OF SOCIO-TECHNICAL REGIMES

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Abstract

In the face of dangerous anthropogenic climate interference, understanding how to transition carbon intensive systems, such as the electricity sector, to a lower carbon state becomes increasingly important. Many of such systems should be thought of as socio-technical regimes, which consist of networks and complex dynamics between for example policy, industry, consumer expectations, institutions, civil society and culture. These regimes can be highly resilient against radical change. This thesis aims to improve our understanding of the drivers of such resilience by presenting a new theory centered on the idea of transition costs. A heuristic framework is presented discussing how transition costs act as barriers between the path of an existing regime and visions of alternative paths. The new theory explains how transition costs are created and reinforce one-another; it thereby goes beyond previous work on lock-in and spillover effects and complements Geels' (2012) framework on multi-level perspective (MLP). Based on the transition cost theory an analytical framework has been derived, categorizing the costs into policy spheres. The new framework is employed in order to analyze transition costs in the German electricity sector and the risk of policy interventions creating future transition costs. It is concluded that the German electricity sector faces high transition costs; however there is a window of opportunity currently opening. In this context a policy package aiming at several elements of the regime is discussed. The theory and framework presented herein has the potential to improve policy making on the matter of transition of socio-technical regimes and in particular to ameliorate policy timing and avoiding future transition costs.

Table of Content

1 Introduction **7**

1.1 Research Objective and Outline **8**

1.2 Research Background **10**

1.2.1 Path Dependent Processes 10

1.2.2 Switching Cost and Barriers to Change 15

1.2.3 Transition of Systems 18

2 New Theory on Transition Costs **21**

2.1 Transition Costs: A Heuristic Framework **22**

2.2 Drivers of Transition Costs **25**

2.2.1 Governing Mechanisms of Transition Costs 25

2.2.2 The Dual Role of Spillover Effects 28

2.3 Categorizing Transition Costs **33**

2.4 Reinforcement Mechanisms **39**

2.5 Transition Costs as a Function of Time **42**

2.6 Conclusion **46**

3 Application **48**

3.1 Transition Costs in a Carbon-Intensive Electricity Sector **48**

3.1.1 Structural Transition Costs 49

3.1.2 Capital Transition Costs 51

3.1.3 Conclusion 55

3.2 Policy Comparison: Risk of Creating Future Transition Costs **55**

3.2.1 Deployment Subsidies 57

3.2.2 Research and Development Subsidies 62

3.2.3 Conclusion 67

4 Conclusion 68
4.1 Consequences for Policies 69
4.2 Limitation and Future Research 70
5 Bibliography 73
Appendix A – List of Barriers to Energy Markets 78

Table of Figures

FIGURE 1 - HIERARCHY OF RESEARCH QUESTIONS 9
FIGURE 2 - PATH DEPENDENT PROCESS WITH ABSORPTIVE BOUNDARIES 10
FIGURE 3 - PATH DEPENDENCY MODEL FOR LOCAL INDUSTRIAL EVOLUTION 13
FIGURE 4 - HEURISTIC FRAMEWORK FOR MLP; 19
FIGURE 5 - HEURISTIC FRAMEWORK FOR TRANSITION COST THEORY 23
FIGURE 6 - TRANSACTION COST CREATING MECHANISMS 26
FIGURE 7 - CATEGORIZATION OF TC I 33
FIGURE 8 - CATEGORIZATION OF TC II 35
FIGURE 9 - CATEGORIZATION OF TC III 36
FIGURE 10 - REINFORCING MECHANISMS BETWEEN TC 39
FIGURE 11 - TC AS A FUNCTION OF TIME, INVESTMENTS AND INTER-PATH SPILLOVER 42
FIGURE 12 - TIMING OF SUBSIDY 44
FIGURE 13 - CAPITAL TC FOR GERMANY'S ELECTRICITY SECTOR 52
FIGURE 14 - ILLUSTRATION OF FIT 56
FIGURE 15 - EFFECT OF FIT ON TC 58
FIGURE 16 - EFFECT OF R&D SUBSIDIES ON TC 65

Table of Tables

TABLE 1 - SPILLOVER EFFECTS 29
TABLE 2 - PRELIMINARY LIST OF TRANSACTION COST 32

List of Abbreviations

CO2e	Carbon Dioxide Equivalent
EIB	European Investment Bank
FIT	Feed-in-Tariff
Gt	Giga Tones
IEA	International Energy Agency
LLKS	Long-lived Capital Stock
MLP	Multi-Level Perspective
R&D	Research and Development
SLKS	Short-lived Capital Stock
TC	Transition Costs
WB	World Bank
WW2	World War 2

1 Introduction

Over the last few decades avoiding dangerous anthropogenic interference into the climate system (United Nations 1992) has emerged as one of the major challenges of the 21st century. In order to keep the probability of a global temperature increase of 2 degrees Celsius below 50% the cumulative emissions of CO_2e has to be capped at less than 1500 Gt (Meinshausen et al. 2009). With 41% (IEA 2012) globally, electricity and heat generation is the major single source for CO_2e emission. This is mainly driven by the use of coal and peat as fuel, which contributes 72% of those emissions. Thus the question arises how the transition of the electricity sector to a lower carbon state can be facilitated. In some countries, such as Germany and Australia, renewable energy sources have already reached grid parity (Bloomberg New Energy Finance 2012). Despite these developments renewable energy still only contributed 4.7% to the total electricity generation in 2012 (BP: Statistical Review 2012).

In this context a recent report of the World Bank (WB: Shalizi & Lecocq 2009) argues that the energy sector is "locked-in" to fossil fuels, due to its carbon intensive long-lived capital stock (LLKS). Besides overcoming such a lock-in in western countries, where LLKS has been built up over decades, authors have pointed out the urgency of avoiding further lock-in of emerging economies (Shalizi & Lecocq 2009; Helm 2012). On the issue of carbon lock-in (Unruh 2000) has argued that the co-evolution between technological and institutional systems creates resilience to change and eventually locks the system in. A recent paper of the European Investment Bank argued that knowledge and institutional lock-in, as well as path dependency and network externalities, create resilience of LLKS. While all these authors agree on the importance of understanding the origin and implications of the resilience of carbon intensive systems, there is a clear lack of common definition of lock-in and the dynamics governing it.

The origins of this term reach back to Arthur et al. (1987) and David's (1985; 1988) works on path dependent processes. Arthur et al. (1989; 1987) has shown that given increasing returns to adaptation early random events in the competition between two initially equal goods or systems can lead to the dominance of one over the other. If this occurs to the extent that the differential of increasing returns is large enough to make the majority of customers switch to one innovation a dominant design will emerge. This state has been described as lock-in. David (2005) stated that later authors have avoided clearly defining the term lock-in, which has let to conflicting or diverging application of the term. In light of the increasing importance of investigating how to foster the transition of highly resilient carbon intensive systems, a common understanding of the definition of such resilience and the mechanisms creating resilience is needed. This thesis contributes to the field by offering a new theory on resilience of socio-technical systems centered on the idea of transition costs.

1.1 Research Objective and Outline

This thesis is structured along a hierarchy of objectives (figure 1). The overarching objective is to contribute to our understanding of inertia of socio-technical regimes and how transition of such regimes can be fostered given such inertia.

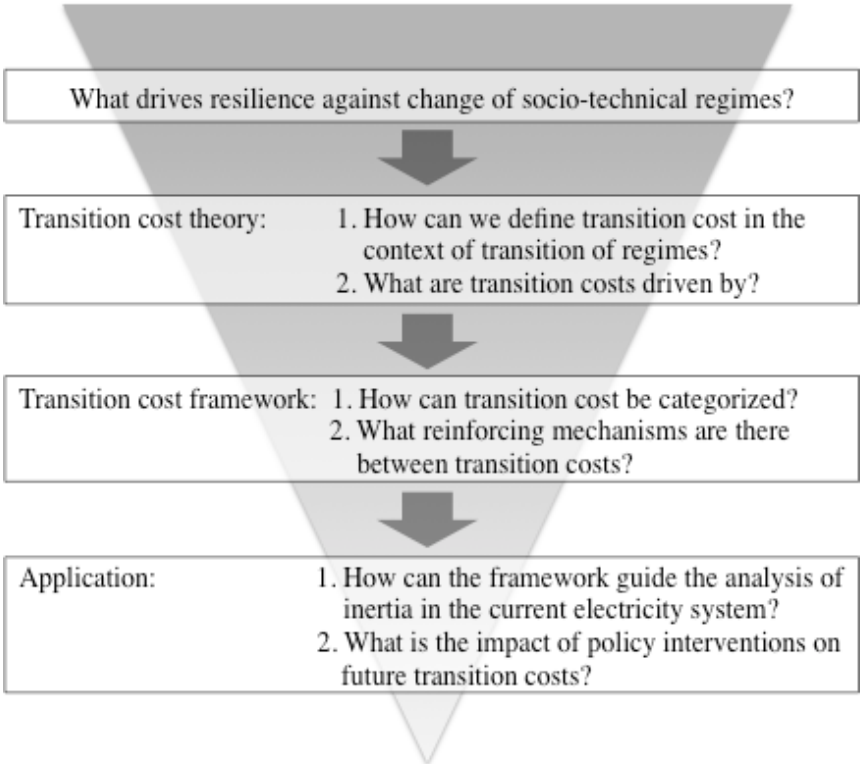

Figure 1 - Hierarchy of research questions; Source: Created by author

The first chapter will provide research background on path dependency, switching costs and system transition theory. The second chapter presents a new theory explaining how resilience to change of socio-technical systems can be defined and what it is driven by, centered on the idea of transition costs. The Third chapter presents an analytical framework, based on a categorization of such transition costs. The framework is focused on guiding policy analysis on the question of how transition costs can be overcome or avoided in order to foster the desired transition of socio-technical regimes. The fourth chapter will apply the analytical framework to analyze the transition costs in the existing electricity system. Based on those results a second section will compare the risk of two policy tools in creating future transition costs. The final chapter offers a concluding discussion and open questions for future research.

1.2 Research Background

This section is structured in three sections. The first section will introduce studies on path dependency, which builds the groundwork of this thesis. The second section will discuss the concept of switching costs and barriers to change as it has been used in previous publications. It will be argued that the previous studies focused on a rather narrow definition of the concept. Furthermore, many initially separate theories on switching costs and barriers have been converging over time, in order to better understand the inertia for systems towards change. The third section focuses on literature that takes a more holistic system approach rather than analyzing markets or sectors.

1.2.1 Path Dependent Processes

Economic history provides many examples of initially equal innovations competing for diffusion in the market. Among the most prominent are the competitions between AC and DC currents in the late 19^{th} century (Hughes 1983), electric and combustion engines for vehicles (Mowery & Rosenberg 1999), and more recently VHS video technology and other formats (Liebowitz & Margolis 1995). In each one of these examples over time a dominant technology emerged capturing the vast majority of the market share. Arthur's et al. (1994; 1987; 1989) and David's (1985; 1988; 2005) work on path dependency under increasing returns offers insight into the extent to which early random events can significantly influence the competition between two equal innovations.

In the late 1980s the idea gained popularity that economics needed a new set of theories and tools that were better able to grasp the evolutionary processes. In

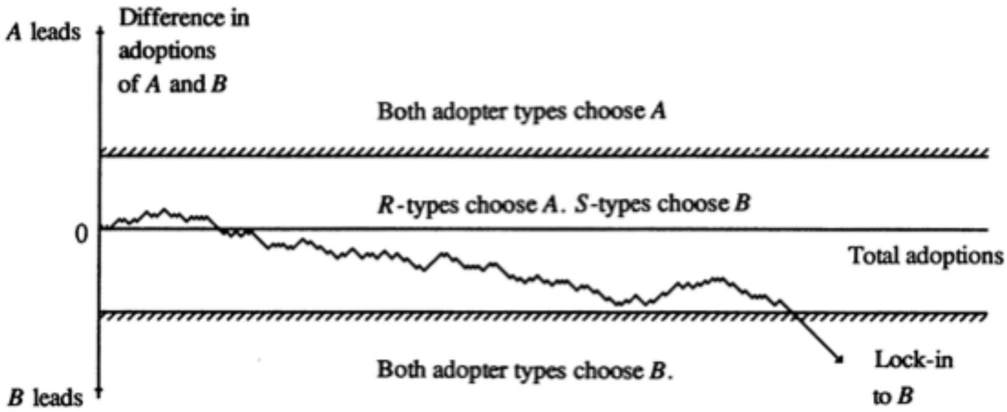

Figure 2 - Path dependent process with absorptive boundaries; Source: Arthur (1989)

neoclassic economics the path leading to a certain state has no influence on the properties on this state, meaning that the state has no memory of how it has been created (Harris 2004). In contrast to this view path dependency theory considers the influence a path (historical events) has on the properties of a system. This section will focus Paul David and Brian Arthur's works as one of the leading contributors to path dependency theory in economics and discuss Martin's criticism of their work.

The origin of path dependency stems from natural science studies on evolutionary processes. However, a study from Eggenberger & Polya (1923) can be regarded as the basis for Arthur's work on path dependency in economics. Eggenberger & Polya (1923) proved that in a path-dependent process with a self-reinforcing mechanism small random initial variation fundamentally change the final state of the system. Arthur (1989) applies these findings to economic theory in order to explain the dominance of certain designs or technologies. Analogous to the Polya system he shows that when assuming two consumer groups each initially favoring one of two competing designs with increasing returns to adaptation, thus self-reinforcing, initial random variation in adaptation of both technologies can lead to a lock-in to one design. This occurs if increasing returns, triggered by initial variation in deployment, reach a point by which one technology yields higher utility for the majority of consumers. Lock-in is therein defined as the threshold at which the majority of consumers switches to the further developed system, which changes the path of the system from a random walk–to the dominance of one driven by increasing returns (figure 2). He argues that the outcome of such a process has the following three properties: non-predictability, non-superiority, and non-ergodicity, meaning not forgiving of early events.

This initial theory is further refined in his later book on increasing returns and path dependency (Arthur et al. 1994). He emends the original binary definition of lock-in by stating that *"[a system is] locked-in to a degree measurable by the minimum cost to effect changeover to an alternative equilibrium."* This definition describes lock-in as a continuum of changeover costs rather than a binary state. Further, he argues that a system as defined above can have multiple equilibria. Initial random variation might push the system towards a local minimum and thus prevent it from reaching the long-term global minimum. In this context exit regrets occur if one path is being pursued because it yields initially high returns to adaptation; however in the long run another path would have led to the global minimum. At the core of Arthur's theory is the notion that path dependent processes are subject to increasing returns of adaptation. He defines four such sources of increasing returns: scale, learning, coordination effects and adaptive expectations (Martin 2010). In many aspects David's models on path dependency overlap with Arthur's, however he defines network externalities as the main driver for reinforcing processes. He argues that technical interrelatedness, economy of scale and the quasi irreversibility of past investments are all elements of network externalities, which contribute to technological lock-ins (David 1985; 2005). Further David introduces the notion of "basins of attraction", describing "one of multiple equilibriums" a state can lock in to. (Martin 2010).

Martin (2010) criticizes Arthur and David's notion of lock-in as "*the convergence to a historically dependent equilibrium*" (Martin 2010: p.8), as empirically such equilibria are very uncommon. He argues that research on life-cycles of industries has shown that path-dependent systems may not be locked-in to one equilibrium but rather evolve incrementally. Going one step further he states that "*retaining [the] notions of equilibrium [as] defining path dependence and lock-in seems to run counter to the key tenets of evolutionary economics*" (Martin, 2010: p.10). Based on this criticism he proposes an alternative path dependency model through which to understand local industrial evolution, in absence of a notion of any equilibrium state (figure 3). The model considers two contrary dynamics stemming from an established path. On one hand the system is self-reinforcing, thereby stabilizing and constraining new innovations. On the other hand the system is evolving incrementally through conversion, layering and recombination, thus enabling new innovations (Martin 2010).

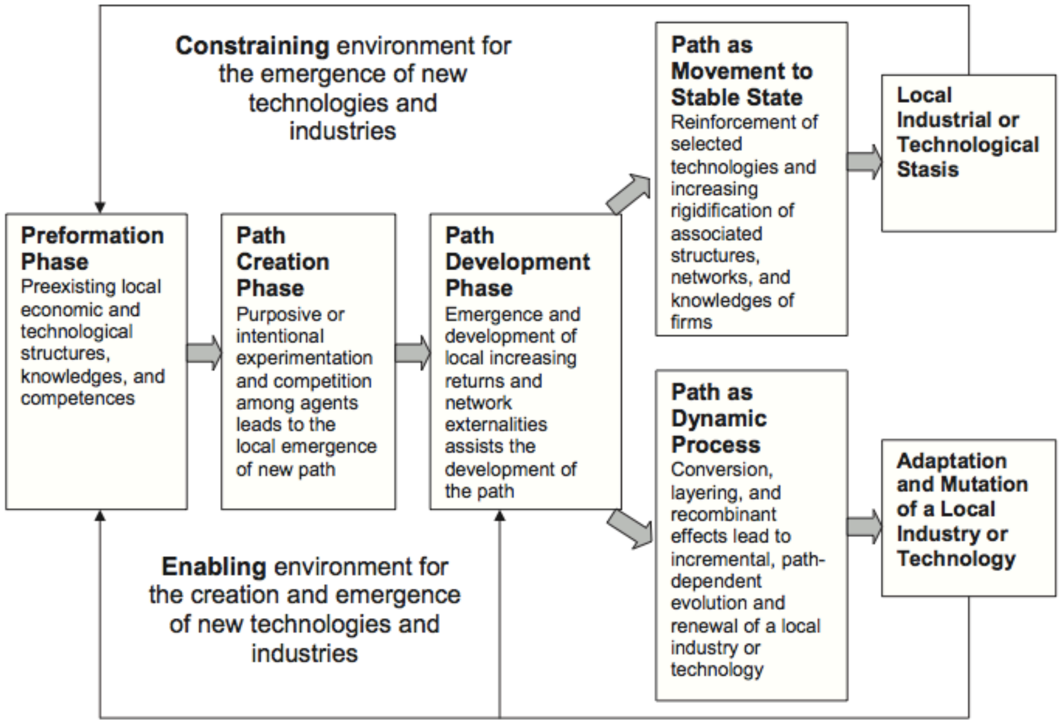

Figure 3 - Path dependency model for local industrial evolution; Source: Martin (2010)

Martin's work is an important contribution to our understanding of path-dependent systems in absence of the notion of equilibrium. Although, as David (2005) has noted, even within Martin's paradigm it is possible that systems go through temporary stages of equilibrium. In this context Martin's model raises an important question, how can we understand the stability or inertia of such systems in the absence of a notion of equilibrium state? As the following sections will show this question is implicitly and explicitly connected to much of the work on switching costs, barriers and system transition frameworks.

1.2.2 Switching Cost and Barriers to Change

In the late 1980s a series of papers debated the impact of switching cost on competition and welfare. Two of the leading authors in that field are Weiszäcker (1984) and Klemperer (Farrell & Klemperer 2007; Klemperer 1987). Originally this school of thought developed parallel to the work of Arthur and David, using different language and methodologies. However Klemperer's later publications on switching costs mention them as drivers for states of lock-in as defined by Arthur and David. In his work Klemperer (1987) focuses on switching costs for consumers and competition between goods or companies rather than transition of whole systems. This leads to a rather narrow definition of switching costs as solely stemming from transaction and learning effects. Later he adds network effects as drivers for lock-in but separates these effects from switching costs (Klemperer, 2007). In his work lock-in describes a situation where consumers, after having chosen one system or good, face switching cost that prevent them from deviating from their original choice. His main findings are that switching costs can lead to quasi monopolies, which increases price and decreases output. These potentially welfare-reducing states can be overcome by government intervention; however he shows that if switching costs cannot be avoided in the long run a governmental intervention might not be welfare increasing. His studies have contributed to our understanding of the elements of switching costs as well as the connection of switching costs and lock-in. However Klemperer's work does not offer a concise discussion on the origins and constituting elements of switching costs. This is partially driven by his research focus on consumer switching costs, which leads to a rather narrow definition, thus disregarding wider system effects.

Although the term is not very dominant in his work Michael Porter offered valuable insights on the matter of switching costs. Throughout his career Michael Porter (2008) has studied the dynamics of competition between firms and systems. His widely-cited five forces framework discusses threats of new entrants as one of the five elements influencing the dynamics of rivalry. In this context Porter has identified seven barriers to market entrants.

- Supply side economy of scale
- Demand side economy of scale
- Customer switching cost
- Capital request
- Incumbency advantage independent of size
- Unequal access to distribution channels
- Restrictive government policy

Although Porter only explicitly mentions switching costs as customer switching costs, it can be argued that each barrier represents a switching cost from the existing product to the new entrant. Compared to Klemperer (1987) and Weitzäcker (1984) he therefore offers a more detailed analysis of switching costs. Furthermore, Porter's approach differs from the other as he starts to consider the wider socio-economic system surrounding a good or a firm. However, later authors criticized the framework for under-representing the impact of governments and public opinions (Brandenburger & Nalebuff 1997). Porter's papers have spurred a wave of new research. One of the issues that is still being debated is how such barriers can be understood and influenced on a system level.

More specific to the energy sector the IEA (2003) published a list of ten barriers to the adaptation of new energy technologies (Appendix 1). While the authors state that the list is neither exhaustive nor are the barriers mutually exclusive, it adds some new elements to the discussion. First, the list connects many of the barriers to scale, learning and consumer-expectation effects and thereby implicitly relates the topic back to Arthur's sources of increasing returns of adaption. Further, the authors argue that some of the barriers are created by market failures such as externalities and spillover effects. Despite the analysis only scratching at the surface of each of those issues, it provides a good indication for the new discussions arising about the connection of barriers, lock-in and market failure.

Garnaut's (2008; 2011) work can be seen as a bridging element between studies on switching costs and system-level analysis. He argues that a series of market failures at the demonstration and commercialization phase disincentivize first mover behavior. In other words they increase the costs of switching to a new system. He identified five of such spillovers, namely knowledge spillover, skills spillover, regulatory spillover, support sector externalities, social acceptance spillover, and financial market spillover. In the Australian Climate Change Review, he mentions these market failures as major barriers for a transition to low-carbon technologies. One of the questions arising from his studies is how precisely such spillover effects contribute to the inertia of the existing systems and how this mechanism is connected to the work on path dependency and other barriers identified by previous authors

This section discussed previous work on market barriers and switching costs. It aimed at showing how initially separated concepts converged over time towards the issue of how the resilience of established systems can be understood. The following section will present literature focusing on transitions of such systems.

1.2.3 Transition of Systems

Geels and Smith are presented as prominent examples of a wider literature on socio-technical regimes and in particular on transition from such regimes. Within the field the concept of socio-technical regimes is commonly understood as a combination or network of "*technology, policy, markets, consumer practices, infrastructure, cultural meaning and scientific knowledge*" (Geels 2012: p.1). The literature is usually analysis or conceptualizes evolutionary process to improve the understanding on transition of systems, thus it is closely related and regularly draws from path dependency.

Smith's et al. (2005) model of socio-technical transition distinguishes between two governing factors of regime change, namely selection pressures and capacity of the regime to adapt. Selection pressures challenge the existing configuration within the socio-technical regime. Those pressures can arise exogenously, for example from competing regimes, or endogenously, for example by incremental innovations from within the regime. Smith (2005) argues that adaptive capacity depends on the resources available to the regime and the different actors' capabilities to coordinate those resources. Based on those two factors he suggests four typologies of transitions: endogenous renewal, re-orientation of trajectory, emergent transformation and purposive transitions. From a policy perspective each of these transitions is likely to be receptive to a different policy intervention, either to constrain or foster change. Smith presents a concise analysis of several past transitions. His framework offers a structured approach to investigate those changes; however, in order to guide policy makers the framework requires detailed information and to a certain extent foresight about selection pressures and adaptive capacities of existing regimes. Thus for policy his findings are likely to be limited to situations that mimic past transitions in terms of their networks between existing players and selection pressures.

Most recently Geels (2012) published a study on system transition, which presented a new multi-level perspective (MLP) framework. The MLP integrates previous understanding of *"co-evolution and multidimensional interaction between industry, technology, markets, policy and civil society"(Geels 2012: p.1)*, with the aim of offering an analytical framework for the transition of systems. Geels (2012) differentiates between three levels of structuration, niches, socio-technical regimes and socio-technical landscapes. The MLP describes the dynamic of how novelties emerge from niches and start competing with existing regimes, which are *"stabilized by many lock-in mechanisms"* (Geels, 2012: p.2). He does not provide a detailed analysis or clear definition of these lock-in mechanisms. However, he states that they arise from a stabilizing interplay between policy, industry, technology, culture, science and market user preferences. The framework (figure 4) shows the possibility of the landscape and the regime influencing the creation of niche innovations, but these effects are seen as external and the description leaves many questions unanswered, such as the role of spillover effects. Thereby he forgoes the chance to analyze in more detail how financial and social investment signals and spillover effects influence the competition between novelties and the existing social-technical regime. Geels' (2012) study offers a valuable integrated framework to think about transitions of large systems. This thesis complements Geels' (2012) work by analyzing what drives the resilience of existing socio-technical systems to change. It offers a concise framework of such drivers and identifies policy tools to support the novelties in competing with the existing regimes.

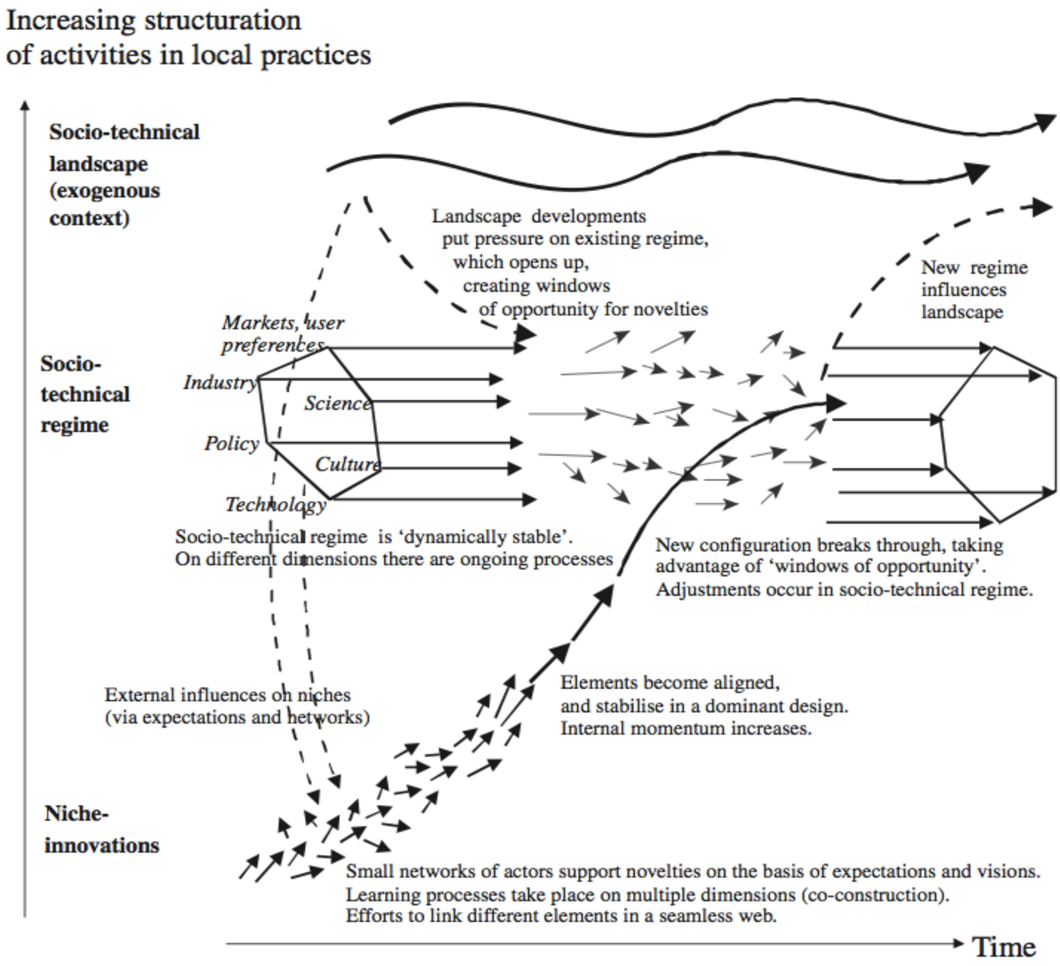

Figure 4 - Heuristic Framework for MLP; Source: Geels (2012)

2 New Theory on Transition Costs

The previous discussion on literature has revealed that the existing theories and frameworks through which we understand and analyze path-dependent processes and resulting lock-ins or switching costs are not sufficient to guide policy or research on the effects of policy tools to overcome a lock-in. Thus, building on the previous work on path dependency (Arthur et al. 1987; 1989: 1994 and David 1985: 1988) and dynamics between existing regimes and novelties (Geels 2012) the following section will present a new theory on transition cost with the aim of establishing an integrated understanding of the drivers of transition costs and thus the possible tools for policy to intervene. The term transition costs (hereafter abbreviated as TC) differs from switching costs as it refers to the transition to entire socio-technical regimes rather than the switching of a good. Moreover, the term *"lock-in"* is not employed in the subsequent thesis because it has a false connotation of irreversibility of the state, which is contrary to the basic motivation of the new theory, namely improving our understanding on how to foster change.

This chapter is structured in five sections. The first section will introduce a heuristic framework as the key to the new theory. The second section presents the new integrated understanding on the mechanisms governing TC. The third section will propose a categorization of TC in order to derive a policy analysis framework. The fourth section discusses reinforcing mechanisms between TC. The fifth section analyzes how TC behave over time. It will be argued that some TC are cyclical, and are therefore highly relevant for timing policy. The final section provides a conclusion of the chapter.

2.1 Transition Costs: A Heuristic Framework

This section will introduce a heuristic framework for TC and discuss how this perspective relates to earlier work.

The transition cost theory can be understood as a complement to Geels' (2012) research on MLP. Geels' study focuses on the dynamics between the three levels of structuration, as defined in his earlier paper (Geels 2002). His framework contributes to our understanding of the complexity of dynamics, which govern the evolution of socio-technical regimes. The hereafter-presented theory on transition costs differs from Geels' work in two main ways. First, unlike the MLP the evolutionary process is analyzed from the perspective of the established regime; thus transition costs will be defined as the cumulative costs all actors would bear if the existing socio-technical regime were to transition to another system. Secondly, the focus of the theory is to explain the origins and dynamics governing the resilience of existing regimes against transitioning to another state. It is important to note that this theory does not contradict Geels' framework but rather complements it by providing a shaper heuristic lens for certain dynamics within the broader system Geels describes.

Figure 5 shows the heuristic framework for the proposed transition theory. Socio-technical regime is defined as a network of "*technology, policy, markets, consumer practices, infrastructure, cultural meaning and scientific knowledge*" (Geels, 2012: p.1). An established socio-technical regime develops over time along a path of incremental changes. In line with Geels (2012) this regime is dynamically stable. Meaning that, a multitude of dynamic processes between elements within the regime lead to a constant state of incremental developments but at the same time stabilize it. The resilience of this regime will be expressed in TC. The TC, as plotted on the y-axis can be understood as slopes creating the natural boundaries of the development path of the existing regime. The next section will describe in detail how such TC are created. However, it is important to note that in general there are three main ways these costs change. First, they can be impacted by exogenous shocks such as governmental regulation or subsidies. Secondly, they can change endogenously by dynamics within the existing regime. Finally they are impacted by innovations. Based on Geels' (2012) framework novelties emerge in niches and challenge the existing regimes. In the framework presented here novelties can be understood as creating visions of a path for an alternative socio-technical regimes. The term vision is used as identifying a space of possibilities and a heuristic tool for defining problems, in line with early authors (Berkhout et al. 2004). Novelties can consist of a technological innovation or a new social trend; as these are isolated elements or partial formations of an entire regime they should be interpreted as merely visions of alternatives socio-technical regimes. These visions emerge dynamically parallel to the development path of the existing regime. A vision can evolve into an established regime in two ways. If TC are near zero the regime can transition from its development path to the development path of the novelty. However it is also possible that the existing regime destabilizes, thereby virtually lowering TC to zero, and the alternative system stabilizes. In both cases TC have to be zero or near zero. It is important to note that this is not to say that two competing regimes cannot exist next to each other. For example transport by car and train can be seen as two socio-technical regimes, which in many countries co-exist. However from the perspective of one regime the other one creates a vision of how it could substitute its function. Transition costs in this context act as barriers or create inertia of the system to be substituted.

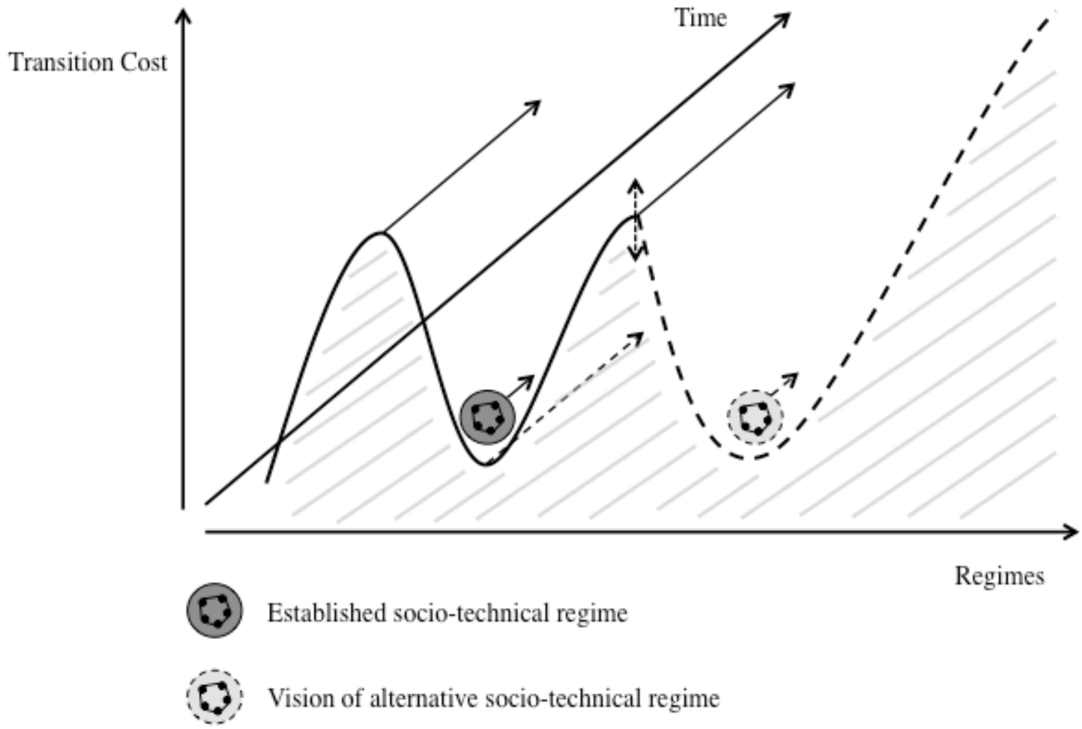

Figure 5 - Heuristic Framework for Transition Cost Theory; Source: Created by author

This section introduced the heuristic framework of the proposed theory on TC. It is important to note that, like any visualization of complex dynamics, figure 5 is a simplification. In particular one should be aware that the x-axis shows incremental steps rather than a continuum. Therefore, the slopes would be more precisely visualized by straight-line boundaries, however this does not change the understanding of the system. The following section will discuss how transition costs are created, what dynamics they are governed by and how they can be influenced.

2.2 Drivers of Transition Costs

The following section will present and discuss the new theory on TC. The first paragraph will describe the basic mechanism by which TC are created. The second paragraph discusses the dual role spillover effects play to the main mechanism. Finally a preliminary list of TC will be presented.

2.2.1 Governing Mechanisms of Transition Costs

The following paragraph will discuss the mechanisms leading to TC, as shown in figure 6. The schematic shows two groups of TC, one that is created by investments' paths that yield increasing returns and one that follows from assets without increasing returns. First, the mechanism in absence of increasing returns will be described. An investment path is a series of investments directed towards a socio-technical regime. It can either be an investment of financial capital such as in plants or R&D, or it can be an investment of social capital for example in the creation of social norms and standards. Previous authors have argued that *"lock-in"* is created by investment paths, which yield increasing returns (Arthur, 1989). This disregards the case that an investment can create an asset, which is not subject to increasing returns. For example the replacement of an old machine is an investment in an asset but does not necessarily increase manufacturing capacity and therefore scale. However this investment is made under the assumption that the asset will yield certain benefits over its lifetime. In the simplest case these benefits can be a cash flow but they can also be measured in utility, which consumers derives from durable goods. These expectations about future benefits present TC to any good that would make these benefits obsolete. For example, a factory owner who bought a machine today faces higher TC to a new product than the day before, because he would lose the entire cash flow created by the purchased machine (minus any salvage profit). Thus these TC are highest right after the point of investment and decrease over the asset's lifetime. Unlike TC discussed in the next paragraph these costs are therefore a function over time. This kind of TC is the source of the resilience discussed by the WB report on LLKS (WB: Shalizi & Lecocq 2009).

The following paragraph describes TC that are created by investment paths that yield increasing returns. Arthur (1994) identified the following four classes of investments that yield increasing returns: adaptation scale, learning, network and adaptive expectation. An investment stream with any one of these four qualities is therefore creating TC, as exemplified hereafter. A scale-creating investment, for example in manufacturing capacity, reduces the average costs of goods thereby increasing TC to a competing product. Moore (1959) produced empirical evidence of this effect. Investments in learning create a specialized labor force and an accumulation of knowledge, which further increases the costs of switching to another good. Thirdly, investments in creating or maintaining a network yield benefits for all goods that are connected or otherwise make use of this network. A classic example is the creation of a telephone network. Once a critical mass has decided on one design transitioning to another would yield high costs. Finally, investments in adaptive expectations foster the agent's expectation of the future prevalence of this good. In such situations the decisions of the agent reinforce the dominance of the existing good or system and thereby increase TC

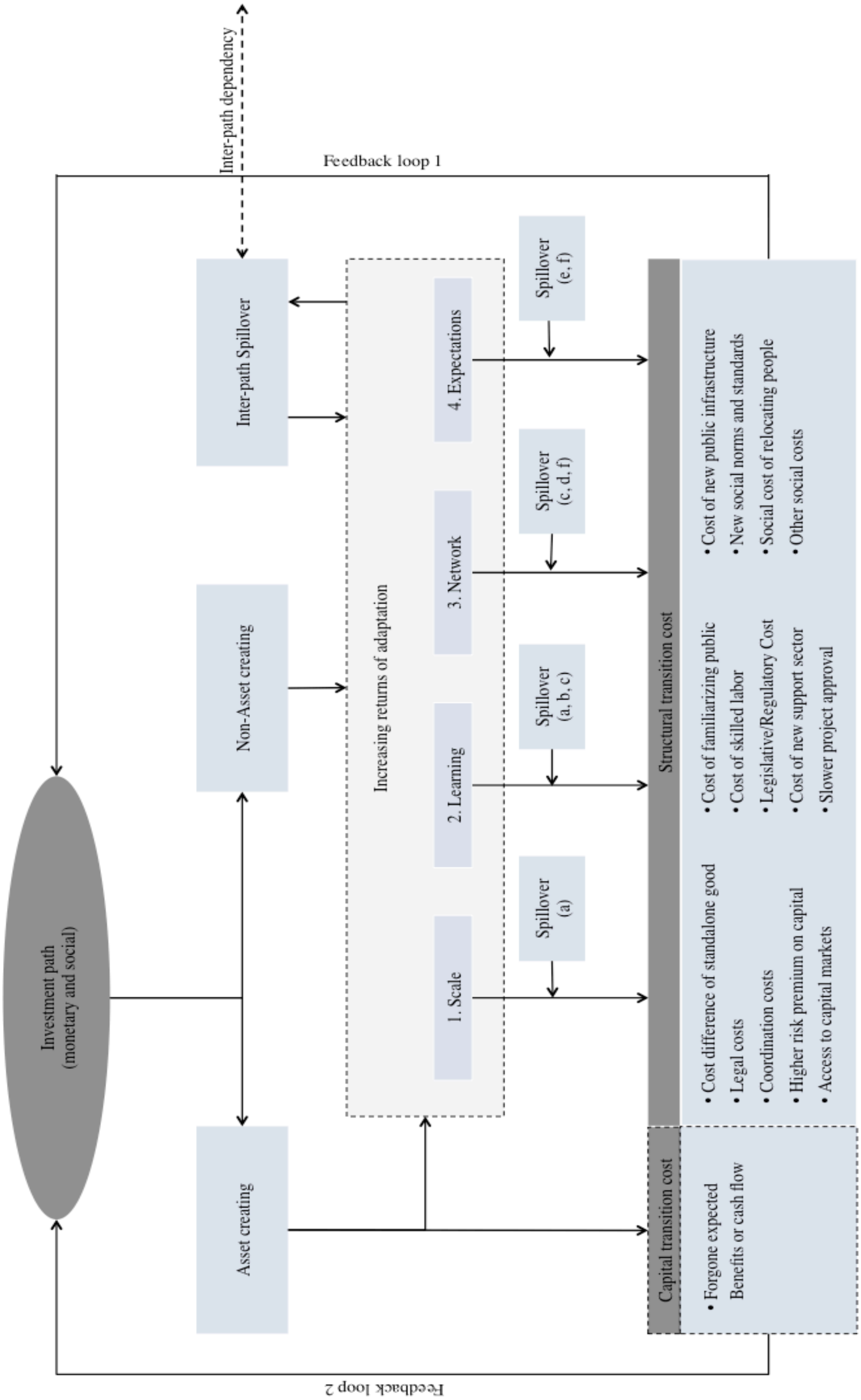

Figure 6 - Transaction Costs creating Mechanisms; Source: Created by Author

Figure 6 shows two feedback loops from TC back to the investment paths. The first feedback loop is based on increasing returns. An investment that is subject to increasing returns of adaptation by definition increases the return of a second investment in the same area compared to the first one and thereby encourages further investments. The feedback loop between capital TC and investment paths function differently. Due to the absence of increasing returns there is no direct incentive for future investments in the same path. However, the expectations about future benefits disincentivize investments in other areas that could jeopardies these benefits. The feedback-loops will be discussed in more detail in the later section on *reinforcing mechanisms.*

The previous paragraph has described the basic mechanism leading to TC. It has discussed under which conditions investment streams lead to TC, and explained that those can be divided into structural and capital TC. This differentiation will be further discussed in the later section. The theory has been discussed using examples of competing goods to illustrate the mechanisms. However the same mechanisms apply to competing socio-technical regimes and novelties as defined by Geels (2012). The following paragraph will discuss the dual role spillover effects play.

2.2.2 The Dual Role of Spillover Effects

As discussed in the literature review, Garnaut (2008, 2011) found that spillover effects disincentivize first mover behavior. This can create TC between existing regimes and novelties. He defined five such spillovers, namely knowledge spillover, skills spillover, regulatory spillover, support sector externalities, social acceptance spillover and financial market spillover. In addition to those five, network

Spillover Effect	Description
(a) Knowledge Externalities	*occur when companies benefit from one company or the government having made the potentially high initial investments to move from invention to innovation and thus demonstrate the commercialization of a good. However knowledge externalities can also occur later from continuous R&D activities, due to the inability of companies to appropriate the entire return on their R&D investments*
(b) Skills Spillover	*exists if firms in established markets can rely on access to skilled labor, while an early mover would bear high costs for hiring and training labor*
(c) Regulatory and Legal Spillover	*exists if firms in established markets can rely on access to skilled labor, while an early mover would bear high costs for hiring and training labor.*
(d) Support Sector Externalities	*are as previously argued a special case of network externalities. The build up of a specialized support sector takes times and potentially high investments. Once in existence it reduces costs for the whole industry.*
(e) Social Acceptance Spillover	*occurs due to the advantage later firms have from initial investments of early movers in familiarizing the wider society with the good. Parts of this category are also social standards and norms about how and when the good is used.*
(f) Network Externalities	*occurs due to the advantage later firms have from initial investments of early movers in familiarizing the wider society with the good. Parts of this category are also social standards and norms about how and when the good is used.*

Table 1 - Spillover Effects; Source: Partially based on Garnaut (2008)

externalities will be added to the list of spillover effect. Arguably support sector externalities are vertical industry networks and could therefore be classified as network externalities. Therefore network externalities will herein be limited to spillover effects from infrastructure and networks created by standards. Examples for this category are road, electric grid or phone networks. The following table (1) provides definitions for each of the spillovers.

If these market failures occur along one of the previously defined investment paths they amplify the TC resulting from the investment. For example investments in research can decrease the costs of a good compared to another. If this knowledge created by the research were to spillover to other firms it would reduce the costs of a new firm focusing on the same good compared to first movers. Therefore the spillover effect increases the TC resulting from the investment in learning. The relationship of these market failures to the existing previously illustrated mechanism is best described as moderating, as figure 6 depicts.

The second role spillover effects play is a more direct one. Cowan & Hultén (1996) has argued that development paths can be interconnected, for example, if they are based on the same basic technology or use the same infrastructure. Given such a case of inter-path dependency the investment in one path can spillover to another path. Such a spillover would act directly as an investment in the other good or systems development, thereby potentially increasing TC to competing goods. This mechanism is reciprocal. An example for such inter-path dependency is the development of the silicon wafer supply infrastructure for PV cells. The computer chip industry requires similar inputs, which decreased the costs of sourcing for the later evolving PV industry.

The last paragraphs were aimed at establishing the basic mechanism that governs the creation of TC. The following paragraph will analyze the variety of TC in more detail. Table 2 provides an overview of the main TC. Depending on the level of abstraction one has chosen some of them can be grouped together or broken down into separate ones. The majority of these costs can be labeled private costs, meaning that these are actual economic costs that are borne by firms, individuals or governments. However some TC are social costs, for example the costs of identity loss when re-locating or re-training people. The table also provides information about the kind of investment and market failure involved in creating the cost. Future studies should test and complete this list by means of empirical research. Unfortunately such undertaking is out of the scope of this thesis. Therefore the following chapter will be based on these TC.

This section described the mechanism by which TC are created. By doing so it brought together previous work on path dependency as well as studies on spillover in the innovation chain and frameworks for socio-technical system analysis. The final paragraph provided a preliminary list of TC created by the process. The next section will discuss various ways of categorizing these costs in order to derive an analytical framework.

Switching Cost	Description	Investment Path	Potential Market Failure
Cost difference of goods	• *Compares standalone goods excluding possible network effects* • *Assuming that goods provide same utility*	• *Scale* • *Learning*	• *a, b and c*
Legal costs	• *Higher legal costs at firm level due to lack of standards*	• *Network* • *Learning*	• *a, b, c, d and f*
Coordination costs	• *Costs of coordinating the switch to a new network or technology*	• *Network*	• *c, d and f*
Higher risk premium on capital	• *Costs arising from higher costs of capital of new firms or innovative projects*	• *Network* • *Adaptive expectations*	• *c, d, e and f*
Access to capital markets	• *Lack of access to capital markets due to scale*	• *Scale*	• *a*
Slower project approval	• *Slower approval of loans for projects due to higher uncertainty*	• *Learning*	• *a, b and c*
Cost of familiarizing public	• *Costs of informing and educating public about an innovation* • *Establishing customer relationships*	• *Adaptive Expectation* • *Network*	• *c, d, e and f*
Cost of skilled labor	• *Higher training and education costs for skilled labor*	• *Learning*	• *a, b and c*
Legislative/ Regulatory Cost	• *Costs of crafting new regulation include legal costs as well as costs for politicians*	• *Network* • *Learning*	• *a, b, c, d and f*
Cost of new support sector	• *Higher cost of information in order to find supplier* • *Higher transaction costs due to lack of relationship and established standards*	• *Network* • *Learning*	• *a, b, c, d and f*
Cost of new public infrastructure	• *Cost of building new infrastructure* • *Foregone revenue from existing infrastructure or additional scrapping costs*	• *Network*	• *c, d and f*
Foregone cash flow	• *Forgone cash flows from existing productive capital* • *Revaluation of knowledge stock*	• *Scale* • *Learning*	• *a, b and c*
New social norms and standards	• *Social costs for learning new norms and standards*	• *Adaptive Expectation*	• *e and f*
Other social costs	• *Includes all social costs arising from possible re-training, re-locating people*	• *Adaptive Expectation*	• *e and f*

Table 2 - Preliminary List of Transaction Costs; Source: Created by Author

2.3 Categorizing Transition Costs

The previous section established how TC can be defined and what they are driven by. It concluded with a list of TC. This section aims at deriving an analytical framework by logically grouping them. The goal of the framework is to support a structured analysis of situations with high TC, in order to better understand how to overcome them or avoid them in the first place. Depending on the focus of the analysis different categorization might best support a structured analysis. Therefore three examples of possible arrangements will be presented in this section. The discussion is separated in two paragraphs. The first paragraph presents three alternative ways to categorize TC. Each categorization supports the analysis of a different research question. The focus of the discussion will be on the third categorization, which aims at policy analysis. The second paragraph discusses the interconnection and reinforcing mechanisms between the different TC

The following paragraph will present three possible ways of grouping TC. These should be understood as three examples out of many potential configurations. Future research should aim at gathering empirical evidence by interviewing representatives of academia, industry and politics, in order to improve our understanding of the most suitable framework. As such an in-depth study is out of the scope of this thesis, the comparison of different configurations is used to improve the final selection. The first one is based on the four investment categories: scale, learning, network and adaptive expectation. The second one differentiates between technological and institutional TC. This grouping is inspired by studies investigating the co-evolution between technological systems and institutions. The final categorization distinguishes between technological, public, financial and capital TC.

It thereby aims at structuring TC in-to three different policy spheres as well as differentiating between time dependent and time independent costs.

Based on the previous discussion on investment paths with increasing returns, the first example categorizes TC in-to four categories: scale, learning, network and adaptive expectations. This configuration can support a well-structured analysis on the sources of TC. A suitable research questions for this framework could for example be: What impact does an investment have on creating TC? Figure 7 provides an illustration of the different categories. One can see that there is certain overlap of the bubbles. This is purely due to the chosen level of abstraction of the TC. For example forgone cash flow can be due to existing productive capital as well as knowledge stock in the form of patents. Therefore forgone cash flow is part of learning and scale. However one could chose a different level of abstraction in order to ensure that the categories are mutually exclusive. In regard to policy analysis, or more specifically

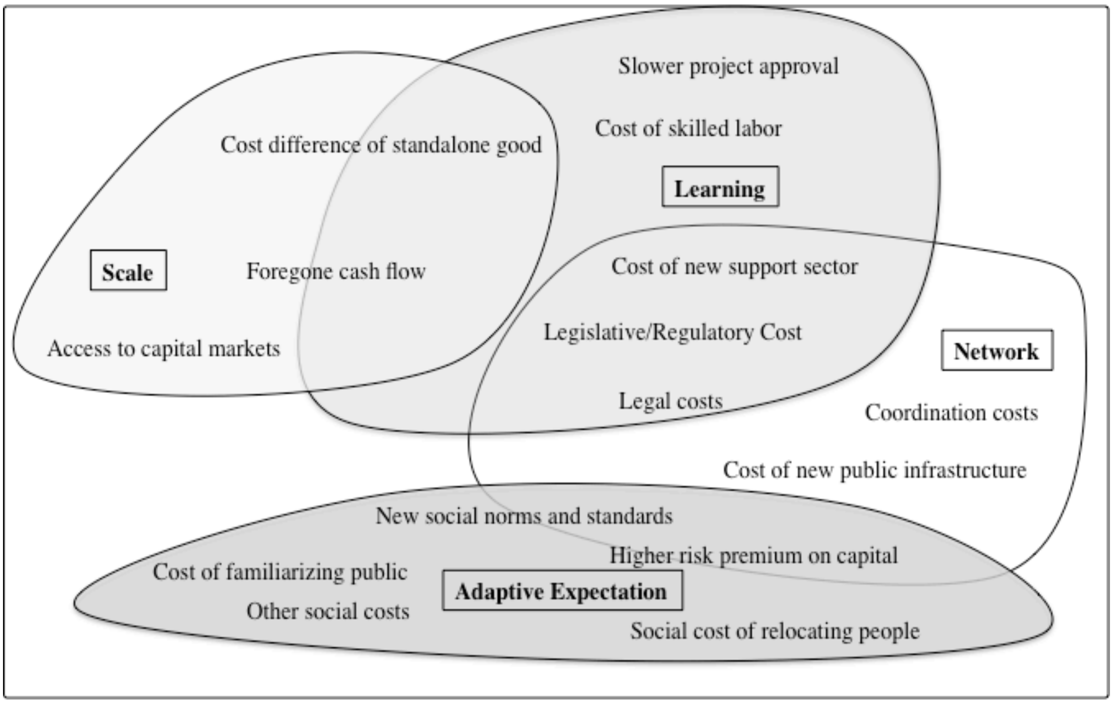

Figure 7 - Categorization of TC I; Source: Created by Author

the comparison between the effectiveness of different policy tools, this framework has two major weaknesses. First it does not distinguish between time dependent and independent TC and thus does not shed light on the importance of policy timing. Secondly, most policies impact a variety of different players, for example industry, financial industry and other interest groups. Often it is important to analyze how each player will react to the policy signal in order to make a judgment on the effectiveness of the policy. For instance a governmental announcement to support a certain technology can be a very strong signal for the financial industry, it can speed up project approval and decrease cost of capital. Furthermore, it can act as a signal for educational institutions to create new courses or abandon others. Thirdly, it is a signal to the consumers about the future of a technology. Just considering these three examples, it becomes apparent that players might fall in more than one category. This is because the above shown categorization does not explicitly distinguish between different players and therefore does not support such an analysis.

The second example (figure 8) is based on previous studies arguing for co-evolutionary processes between technological and institutional systems (Unruh, 2000). In this context Unruh (2000) coined the term *Techno-Institutional-Complex (TIC)* to describe how the emergence of a technology creates demand for institutions that govern it. North (1991) has argued that institutions are subject to the same four effects that create the technological *"lock-in"*, and thereby reinforce it. Drawing from public choice theory (Shughart & Razzolini 2001), it can be argued that institutions have an incentive to hinder the development of any new good that threatens the regime and consequently the existence of the institution itself. In line with this reasoning (Lowi 1979) has shown that even institutions that are meant to regulate a certain technology can eventually have an incentive to foster its development. In this

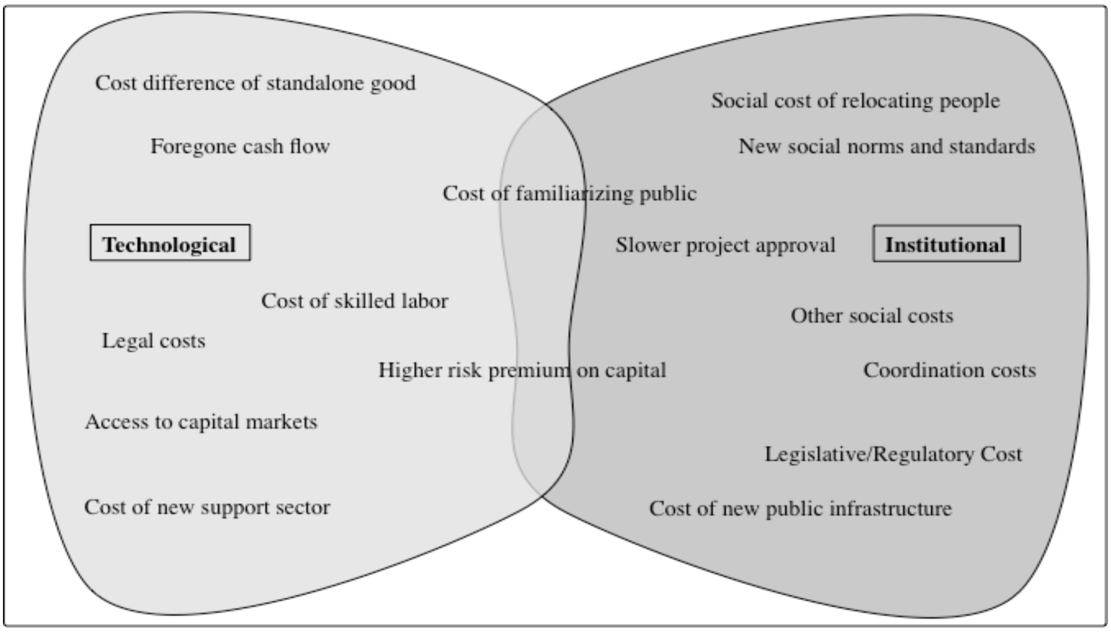

Figure 8 - Categorization of TC II; Source: Created by Author

framework institutional TC include all TC that are not directly borne by the industry. These are mostly costs created by investments in adaptive expectations as well as most created by networks. Technological TC are mainly driven by investments in scale and, partially, in learning. While this framework is suitable for the analysis of co-evolutionary process it is not suitable for policy analysis. In fact it shows the same weakness as the previous grouping. The distinction between different players influenced by policy is too opaque to act as a suitable framework.

The third categorization is aimed at guiding policy and policy research in analyzing the effectiveness of tools for reducing TC. This thesis therefore suggests a categorization along three spheres, namely public, industry and financial and as fourth category capital TC. Figure 9 provides an overview of the different categories. As previously argued Arthur's (1989) categories combine effects that take place in industry like scale and learning effects with effects that occur in the public sphere such as adaptive expectations. Network effects can be created by industry as well as in the public sphere. As these two categories arguably require a very different policy focus an alternative definition of technological TC will be proposed. *Technological TC* combine all those effects that are mainly driven or incurred by industry players.

The second group proposed here is financial TC. This includes all costs that are mainly influenced by decisions in the financial industry, such as lower costs of capital and faster access to capital markets for established technologies. Innovations are usually connected to a higher level of uncertainty compared to established goods. This uncertainty will be priced-in by investors, who will demand a higher risk premium and thus drive up costs of capital. This barrier to compete can for example be observed in the difference between returns on the bond market of Fortune 500 companies and returns expected by venture capitalists (VC). In line with this reasoning Manigart et al. (2002) found empirical evidence that VC in early stage ventures require higher returns that those investing in more developed ventures. In their review of the energy technology innovation system Gallagher et al. (2012) report that the vast majority of investments in the early stage of energy technology diffusion

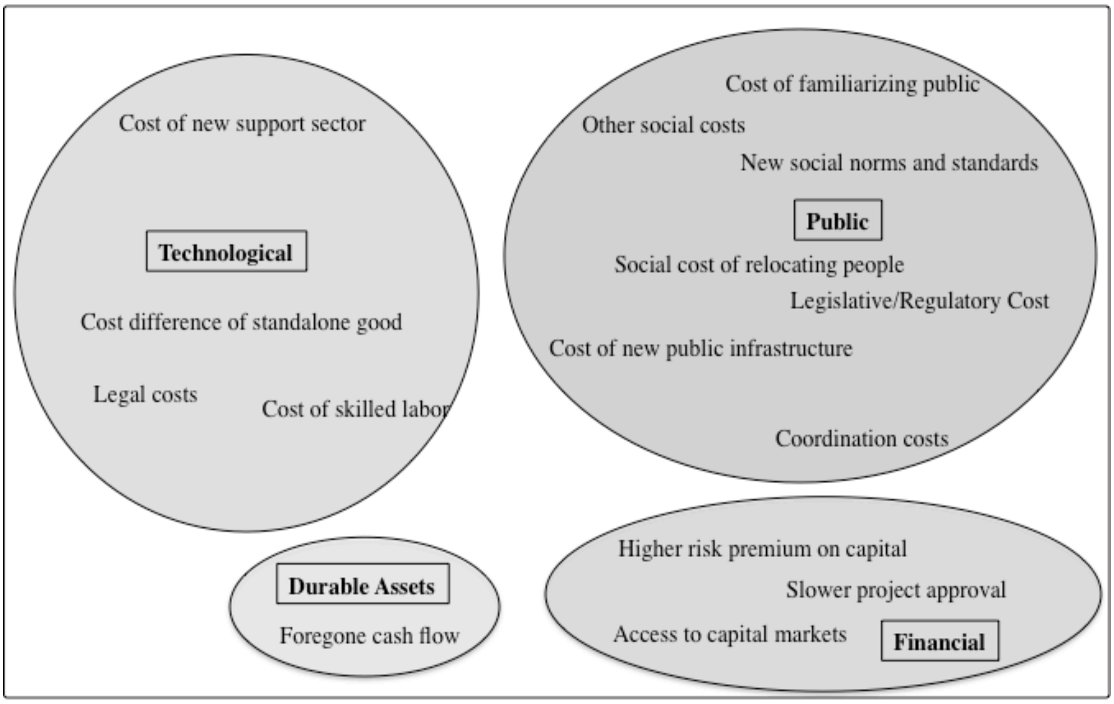

Figure 9 - Categorization of TC III; Source: Created by Author

was made by either governments or venture capitalists and private equity firms. This supports the argument that traditional bank loans or bond markets only gain importance at a later stage of development. The effect can be magnified if innovation spurs from small companies rather than established players. Small companies do not have the opportunity to cross-finance an innovation from existing cash. Furthermore they usually lack access to bond and stock markets due to a lack of scale. The TC do not only exist due to the higher costs of capital but also because of the prolonged time it may require to get financing for a project. This in turn may increase overall costs of the project. It could be argued that this category is merely a subcategory of institutional TC. However unlike the drivers for the institutional TC the financial lock-in is mainly influenced by the financial industry, which requires other policy tools.

The third category is institutional TC and is mainly driven by regulatory and legal costs, costs related to social acceptance and infrastructure investments. These elements are all mainly influenced by public action either through government or civil society. It has a great overlap with the institutional category defined in the previous example. The main difference is that financial institutions have been carved out as separate sphere.

These three categories make up the structural TC, which will be discussed in the next section. The final category includes TC based on capital and is therefore time dependent. The following example is aimed at illustrating the cyclical nature of these TC. Assume there are two goods A and B while A is currently the dominant design and society incurs TC from transition A to B. Given the government wants to influence a transition from A to B and implements an incentive to switch, for example a subsidy for B. If a consumer has purchased good A the day before the subsidy is being introduced, he/she is less likely to be receptive to the subsidy than before the investment. This can be due to scrapping cost are purely due to forgone cash flow. However the closer it gets to the end of the lifetime of good A the more likely the consumer would be to switch to B given the subsidy is equal or higher than the structural TC. In this simple example the government could have implemented the policy at a more effective point in time if it had information about the time of purchase and the lifetime of the good. However in a world with many consumers who make their purchases at random points in time this effect may average out. Yet, this is only true if there are no investment cycles. Therefore data about the TC of capital can inform governments on the importance of timing of their policy and also when the right point in time would be, this will be discussed in more detail later on.

2.4 Reinforcement Mechanisms

The previous section has shown how TC can be categorized in different groups in order to derive an analytical framework. Based on the selected categorization this section will discuss the various interconnections and reinforcing mechanisms between the elements within the framework. The first paragraph will discuss the interplay between the investment paths and the groups of TC. The second paragraph is focused on the interplay between the different categories. It will be argued that there are reinforcing mechanisms at play, which can increase the overall TC to another good or system.

Figure 10 shows the interconnections between all elements of the framework. The first reinforcing mechanism is the one described in section 2.2. An investment with increasing return creates TC, which ceteris paribus increases the incentive to

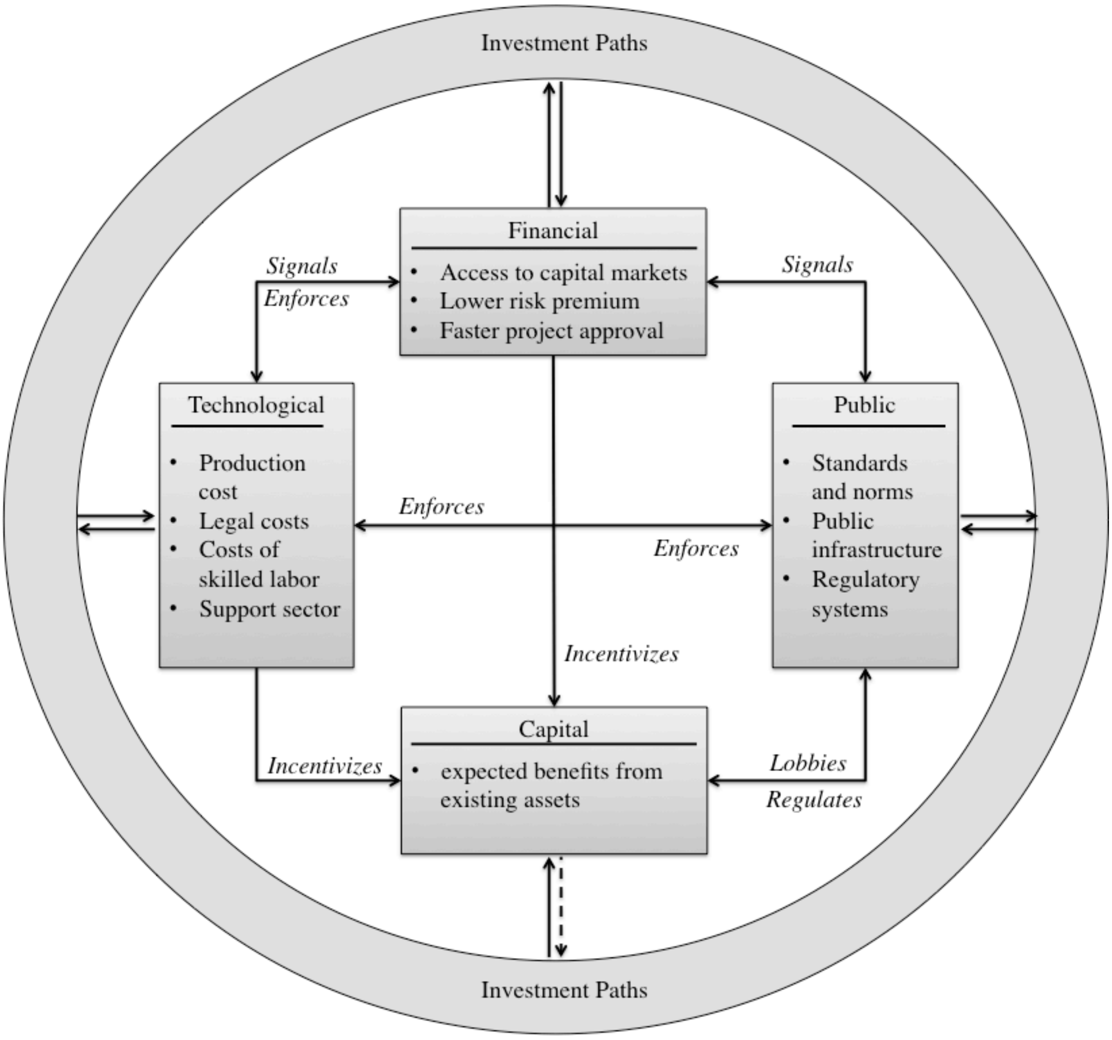

Figure 10 - Reinforcing Mechanisms between TC; Source: Created by Author

direct the next investment at the same good or system. This feedback-loop can act directly, meaning that one TC reinforces itself. However it can also act indirectly, meaning that one TC reinforces another TC, which will be further discussed in the next paragraph. The second loop described in section 2.2 is based on capital TC. In this case TC do not necessarily incentivize another investment in that asset however it does disincentivize investments in a competing good or technology, which would decrease the expected benefits.

The following paragraph describes the indirect interaction between investments and TC as well as the direct reinforcement mechanisms between the different TC. These two are discussed together because they are both reinforcements of one TC category to another, unlike the direct feedback loops explained above.

In the following paragraph each group's impact on the others will be discussed starting with financial TC. An increase in financial TC, ceteris paribus, increases returns on investment in for example new manufacturing capacity. This investment is scale creating and thus increases technological TC. The same mechanism exists for capital TC. In addition, financial TC can act directly as signal to the public or government for example for the need for infrastructure or regulation. On the opposite site public TC can act as strong signal to the financial sector about governmental support or expectations of consumers, which impacts financial TC. Regulation and public infrastructure can also enforce technological TC. For example the decision about roads and rail networks impacts the availability and flexibility of skilled labor. Regulation does also impact expected benefits from existing assets, by for example influencing their lifetimes. The more costly it is to change a regulatory framework the more certain one can be to receive the expected benefits. Expectations about benefits on the other hand increase the incentives to lobby for a supportive regulatory framework and therefore increase transitioning-costs. Technological TC can increase investments in certain assets and thus indirectly increase expected benefits from those assets. High technological TC can also enforce higher financial TC by signaling the long-term dominance of one good or system over competing ones. Finally technological TC can foster public TC through co-evolutionary processes as argued before. It can be concluded that all elements create a highly interconnected web, this is important to recognize for policy makers considering intervention.

2.5 Transition Costs as a Function of Time

The following section discusses how TC change over time. It will be argued that for situations with capital TC related to goods with long lifetimes and high upfront investments timing of policy is very important. The first paragraph will define TC as a function over time, investments and inter-path spillover. Based on this function, the second paragraph will discuss the importance of policy timing for policy to effectively overcome situations with high TC, and what indications there are for the importance of timing.

Based on the previous categorization the following variables will be defined. **Δ**(t, i) is defined as TC from regime a to b, while b is the next best available option. [(C_a-C_b)+ **τ**(i)] represents the technological TC from a to b. The first term is the cost difference between the stand-alone systems given everything else being equal. Tau is the residual technological TC, excluding the cost difference of the good. π(i) stands for the public TC. X(i) represents the financial TC. Finally, **κ**(t, i) are the costs of forgone benefits of a switching to b, depending on time (t), investment (i) and inter-path spillover (p). Based on these definitions the following equation has been derived:

Equation 1:

$$\Delta(t,i,p) = [C_a(i,p) - C_b(i,p) + \tau(i,p)] + \pi(i,p) + \chi(i,p) + \kappa(t,i,p)$$

They can also be calculated as a normalized cost, for example based on system costs:

Equation 2: $$\Delta_n(t,i,p) = \frac{[C_a(i,p) - C_b(i,p) + \tau(i,p)] + \pi(i,p) + \chi(i,p) + \kappa(t,i,p)}{C_a}$$

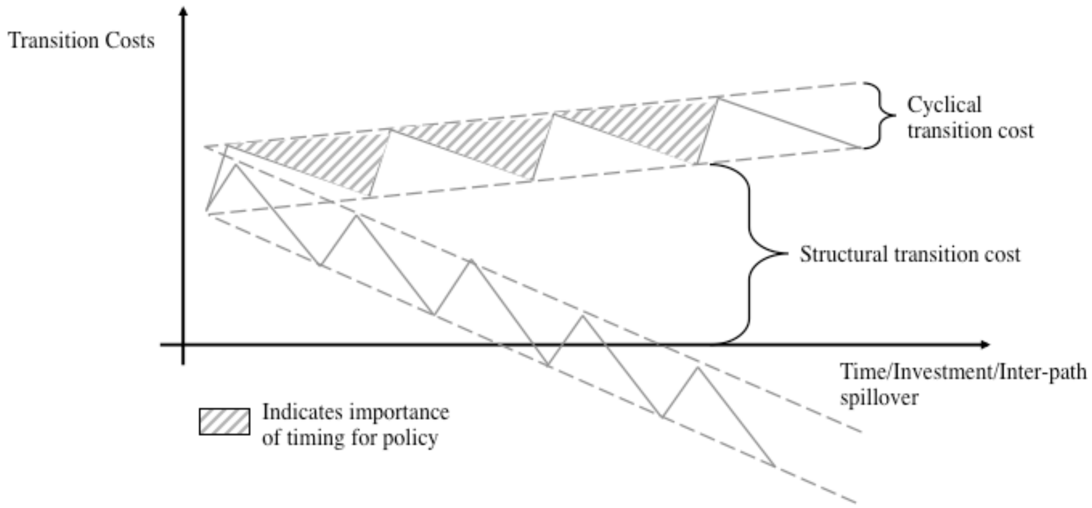

Figure 11 - TC as a Function of Time, Investments and Inter-Path Spillover; Source: Created by Author

It can be stated that additional investments or inter-path spillover, under the previously defined condition, in a good or system lead to higher TC, ceteris paribus. Investments in the competing good b can be understood as negative investments in good a and thus decrease TC. The two cases are shown in figure 11. In the absence of investments the term does not change, therefore it will be called structural TC. The term **κ**(t, i, p) is dependent on investment in the asset and its lifetime. Assuming a fixed expected rate of return the investment determines the expected future benefits. As previously argued the net present value of these benefits decreases over the lifetime of the asset. Figure 11 illustrates the dynamic of these cyclical TC under the assumption of one asset, which is repeatedly invested in at the end of its lifetime.

The previous paragraph aimed at establishing the basic equation of TC over time, investments and inter-path spillover and discussed examples of possible patterns over time. The following paragraph will discuss the consequences for policy resulting from the previous equation and present a measurement for the importance of policy timing. First policies for situations with high structural TC will be discussed. Secondly, policy timing under various cyclical TC scenarios will be investigated.

If a government attempts to foster the change from one regime to another, the above-discussed framework can be used to investigate the relevant TC. Assuming the analysis reveals that structural TC constitute most of the barrier to switch, it follows that some sort of shock or signal will be necessary to bring about dis-incremental change. Such a shock does not have to originate from governmental intervention. For instance, an innovation or a public movement can cause it. Since such events are hard to predict, it will be assumed that the government intervenes. The first question arising from the previous analysis is: which of the three structural TC categories make up the bulk of the costs. If TC arise from the technological sphere, the government has the option to foster learning by R&D subsidies, directly or indirectly, or encourage scale by means of deployment subsidies. The choice between these two policy tools will be discussed in more detail later on. If the major TC arise from the financial sphere the government can either send a strong signal of long-term support for a good and thereby reduce uncertainty or decide to co-finance projects itself to reduce costs of capital. Finally if the public sphere yields the highest TC governments may decide to invest in new infrastructure, undertake public awareness campaigns or rework the existing regulatory framework, depending on the actual outcome of the analysis. The previous policy tools should be interpreted as examples of possible interventions for each of the categories. It provides neither an exhaustive list of possibilities nor are these tools mutually exclusive.

Capital TC constitute a significant portion of the overall TC if the expected benefits and therefore the initial investment into the asset are significant compared to the overall TC. As previously described figure 11 shows a simplified example assuming one asset. It is important to notice that given a system that consists of many assets which are replaced regularly in a random pattern, the capital TC would average out and thus simply shift the structural TC upwards. However a system with few investment-intensive assets and long lifetimes would result in some sort of sawtooth pattern. Assuming that such assets have not been created in even time intervals but following a pattern of investment-intensive periods and less investment-intensive periods, capital TC would be represented by an cyclical wave on top of the structural TC. If the analysis of TC reveals such a pattern it signals that timing of policy intervention in order to overcome TC is highly relevant, because over time the system goes through periods of high and low TC. Figure 12 illustrates a case where a government sets a subsidy high enough to overcome the structural TC. However due to capital TC the subsidy is only sufficient at certain points in time. Depending on the exact mechanism of the subsidy the government has either implemented a rather ineffective policy or in the worst case wasted significant resources on an unsustainable transition.

Having established why policy timing matters, the following equation is presented as measure for the importance of policy timing. The importance of policy timing in regards to TC depends on three factor: the relative amount of investment in the asset, the lifetime of the asset as well as the cyclicality of the investments. These

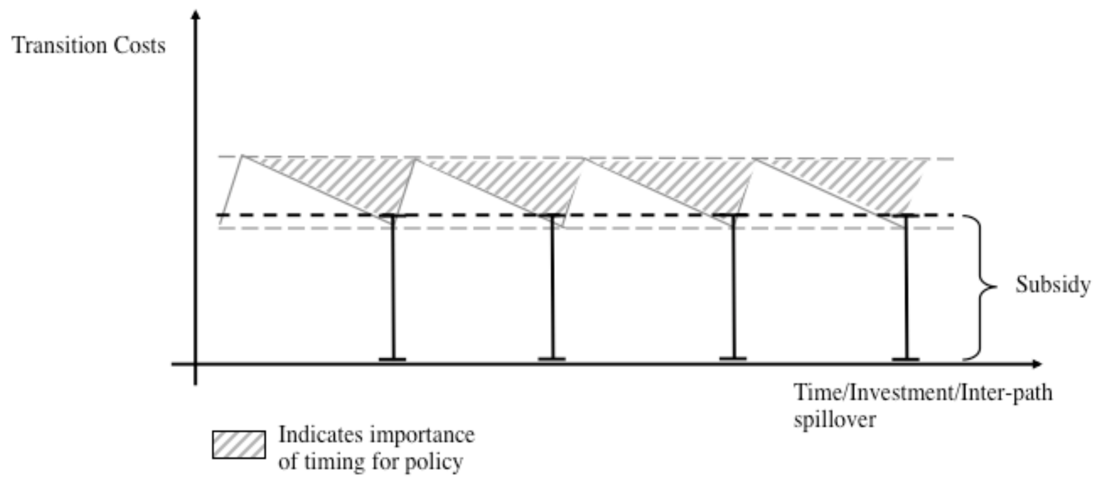

Figure 12 - Timing of Subsidy; Source: Created by Author

three factors together influence the size of the shaded area shown on figure 11 and 12. Therefore the size of the area indicates the importance of the policy timing. The shaded area will be called **φ** and can be calculated with the following equation:

Equation 3: $$\varphi = \Delta(i, p, t_{max}) \times LT - \int_{t}^{t+LT} [\kappa(t, i, p)]\, dt$$

Phi can also be expressed as a normalized measurement based on overall TC:

Equation 4: $$\varphi_n = \frac{\Delta(i,p,t_{max}) \times LT - \int_{t}^{t+LT} [\kappa(t,p,i)]\, dt}{\Delta(i,t,p)}$$

This section has discussed how TC can be expressed in an equation depending on time, investments and inter-path spillover. It has been argued for the importance of policy timing for crafting effective policy to overcome situations with high TC. Finally an independent measure for the importance of policy timing has been derived.

2.6 Conclusion

This chapter presented a new theory on TC with the aim to provide a common understanding on TC, what they are driven by and the governing mechanisms surrounding them. The theory bridges between previous works on switching costs, path dependency theory and system analysis. Furthermore, it provides new insights into the competitive dynamics between existing socio-technical regimes and novelties, and thereby contributes to the recent work of Geels (2012). In order to support policy and industry decision makers in identifying, overcoming and avoiding TC the chapter derived an analytical framework based on the presented theory. The following chapter will offers an application of the framework, by analyzing TC in the electricity sector. Future research should empirically test the TC and their categorization found in this thesis.

3 Applications

The following chapter offers an application of the analytical framework presented in the previous chapter. The first section looks at TC from high to low carbon technologies in a mature carbon-intensive electricity sector. The empirical analysis of capital TC is based on The German electricity sector. It will be argued that policy timing is particularly important for interventions in the electricity sector. The second section will provide a comparative study between R&D and deployment subsidies on the risk of creating future TC. The analysis will show that R&D subsidies bear a lower risk of creating future TC.

3.1 Transition Costs in a Carbon-Intensive Electricity Sector

The following section will analyze the existing TC from high to low carbon technologies. The analysis draws results from studies on the electricity sectors from USA and European countries. While there are important differences between some of these countries, as discussed later, they are all specimens for a developed country with high reliance on fossil fuels and slow projected growth of electricity demand. The analysis is structured in three sub-sections. The first sub-section will discuss initial evidence for the existence of structural TC in the electricity sector. The second sub-section will analyze the capital TC. Based on the results of these analyses the final sub-section will discuss different policy tools. A particular emphasis of the discussion will be on the question of which policy intervention has the least risk of creating new TC in the future.

3.1.1 Structural Transition Costs

Previous authors have argued that the electricity sector is in a state of carbon *"lock-in"* (Unruh, 2000). As argued throughout this thesis, lock-in is not a binary state and should be substituted by the concept of TC. Thus the following sub-section aims at adding to the discussion by analyzing the current state of the electricity sector along the previously defined categories for structural TC.

First technological TC will be discussed. Analyzing data from coal-fired power plants over the last century McNerney et al. (2011) found that the costs for the technology have been subject to continuous scale and learning effects even withstanding increasingly strict environmental regulations. The cost reduction was supported by decades of governmental coal subsidies, which significantly increased the competitiveness of this technology today (Birol 2012). In addition there are several past investments yielding network effects which significantly contribute to today's technological TC. First, the electric grid infrastructure was designed for centralized energy generation, based on the dominance of large-scale fossil fuel or nuclear generation plants. Moreover, the system is supply side managed meaning that fluctuations in the demand are matched by adopting the supply. Such a system favors energy sources that are regulable like fossil fuels. Transitioning to a less controllable electricity source would yield high costs for storage or backup capacity. Secondly, the supply infrastructure for fossil fuels, for example pipelines, rail and shipping routs, has been developed over decades. Much of it is still from the 60s and 70s and has been written of by now which decreases today's costs of these technologies.

This paragraph reviewed some of the indications of the existence of technological TC. As previously discussed, through co-evolution of technologies and institutions a dominant design can foster institutional TC and vice versa, which can create highly resilient socio-technical regimes. Examples for these TC in the electricity sector are the numerous institutions that evolved in order to regulate, support and govern the industry. Institutions can be categorized into three groups. First there are public institutions such as public research institutes and regulatory entities. Secondly, there are private institutes such as industry associations, research institutes or market places (e.g. Henry Hub). Finally, there are social norms and standards. The unbowed continuation of fossil fuel subsidies is a strong signal for the interplay between a dominant design and public institutions. Based on the latest IEA estimate, global fossil fuel subsidies amounted to $523 billion in 2011 (IEA: WEO 2011). These figures certainly require further analysis in terms of their impact; however they do provide an initial insight into to extend of interconnectedness between technology and institutional TC in the electricity sector. A detailed discussion on norms and standards is out of the scope of this study. However standards for quality of fossil fuels as well as trading contracts reduce the costs of these goods.

The third category is financial TC. The majority of western conventional electricity companies are either listed on the stock market or owned by the government (see eg. Dow Jones Utility Average for US or e.on AG, RWE AG and EnBW for Germany). This provides them easy access to capital markets. As previously argued, due to a lack of market access most renewable energy project funding stems from governments or VCs (Gallagher et al. 2012). Manigart et al. (2002) found that VCs require "*a return between 36% and 45% for early-stage and between 26% and 30% for expansion investments, acquisitions, buyouts, and other later-stage categories*". This represents a significant difference in cost of capital and thus provides another barrier to switch to a new low-carbon technology.

The discussion has provided some initial indications for the presence of all three TC in the current electricity sector.

3.1.2 Capital Transition Costs

The following sub-section will discuss capital TC in the German electricity sector. The analysis reveals, that in the 90s Germany entered a phase of constant or even decreasing capital TC. However this window is likely to close within the next decade as large amounts of new assets will have to come online in order to meet future demand.

The analysis is based on the previously discussed definition of capital TC, namely the expected future benefits of existing assets. Based on this definition a detailed study should consider tangible assets in generation, supply industry and distribution infrastructure as well as intangible assets. Due to the scope of this thesis as well as data availability, this section will focus on tangible electricity generation assets only. Future expected benefits are measured as the discounted expected electricity generation over remaining lifetime of the entire capacity installed in any given year. Bundesnetzagentur (2013) publishes data on installation dates and generation capacities, reaching back to 1923. The analysis has been limited to coal, gas and nuclear power plants implying the target to transition away from these electricity sources. The data set includes power plants that are currently not generating but does not include decommissioned ones; thus it is subject to a survivor bias. It is important to be aware of this bias when analyzing the data, as there are at least two events that are not correctly represented by it. First, very early data is likely to underestimate the installed capacity at that time. This is especially true for data before 1945, as many power plants were damaged or destroyed during WW2. Therefore the analysis will only be based on data of the last 60 years. However one should still interpret the steepness of increase in capacity over the first several years with caution. Secondly, the data does not contain the eight nuclear power plants that were decommissioned in 2002 as a result of the 13th amendment to the German Atomic Energy Act (BMU 2002). The power plants were built between 1970 and 1972 and scheduled to go offline between 2010 and 2012, based on an extended lifetime of 40 years (Bundestag 2010). Together they had a capacity of 8 GW. Including them in the data set would increase the steep rise of expected generation in the 70s and result in a relatively sharper decline in the 90s and 2000s. Thus it would support the depicted trend. The expected generation capacity is measured in terra-watt-hours (TWh) and has been calculated based on an 85% load factor, 8765 hours per year and a 7% discount rate. All three assumptions have been adopted from studies by the IEA (2012) and triangulated with data from e.on (e.on 2012). The Royal Academy of Engineering (2004) has published estimated lifetimes for different generation plants. Nuclear has the longest with 50 years, while coal has an estimated 35 and gas merely 25 years. As this study used an average lifetime for coal and gas, four different scenarios were plotted, varying between 25 and 40 years.

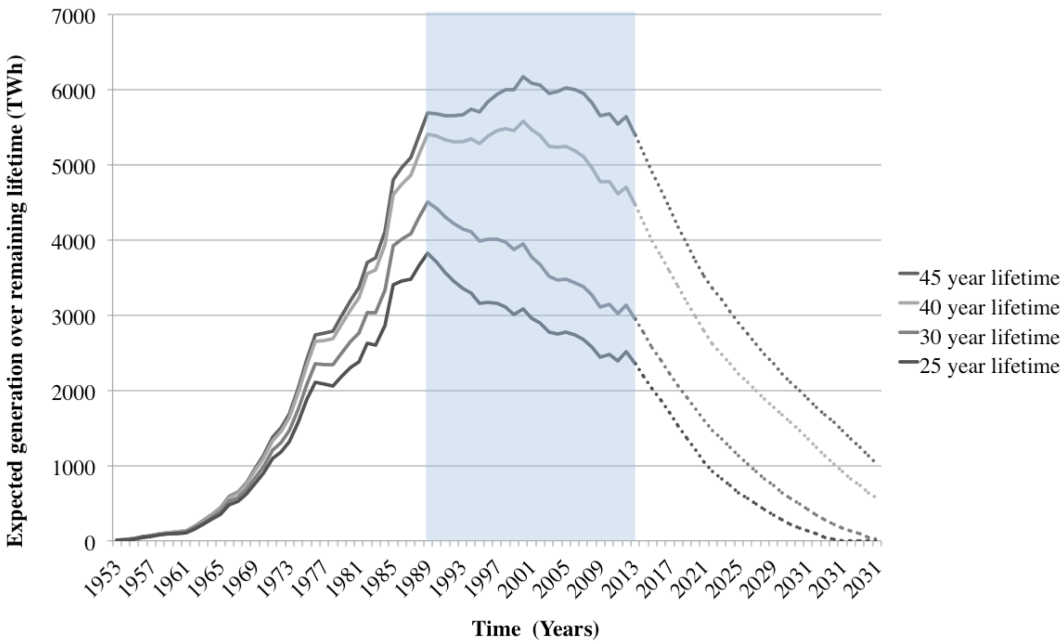

Figure 13 - Capital TC for Germany's Electricity Sector; Source: Created by Author

The remaining nine nuclear power plants have been modeled based on their actual decommissioning dates between 2015 and 2022, as set by the government (Bundestag 2010). Figure 13 shows the expectation curves of four scenarios based on different lifetimes. The graph shows two distinctly different phases. The first phase lasts until 1990 and is characterized by a steep increase in expected future generation. This is driven by a rate of new installment above the rate of aging of existing plants. During this phase the forgone future benefits in case of an immediate transition to another generation technology have increased year by year. The early post-war years were dominated by a strong economic growth and in particular high demand for rebuilding destroyed assets. Therefore, it is likely that this pattern is similar to the trend one would find when analyzing emerging economies, such as China. In the early 90s the balance has shifted leading to a decline or at least stagnation of expected future generation. This does not imply that the actual generation decreases. It merely shows that the existing assets are approaching the end of their lifetime, while new fossil fuel assets have not been built. As previously argued the expected future generation represents TC; therefore it can be concluded that the German electricity system has entered a phase of decreasing TC. This represents a window of opportunity for transitioning to low carbon technologies. These findings are in line with recent reports from the WB (Shalizi & Lecocq 2009) and EIB (Fay et al. 2010), arguing that western countries enter a phase of increased asset renewals in the energy sector. The dotted line represents the future decline given that no new capacity were to be built. It shows that the expected future generation would decrease by 50% over the next 15 years. This is an indication of the urgent demand for new electricity generation assets, which means that the window of opportunity could close quickly in order to keep the lights on. However one has to keep in mind that the graph does not include ca. 22% (BMU 2012) of renewable generation and therefore offers little insight in overall generation capacity.

Three main conclusions can be drawn from the analysis of capital TC. First, when attempting to foster a change in a regime based on high-investment assets with long lifetimes and irregular investment patterns the effectiveness of policy can be improved greatly by analyzing cyclical TC for deciding on policy timing. Secondly, in the case presented here it has been shown that Germany is currently in a phase of low cyclical TC; however this window of opportunity is likely to shut soon. Finally, based on data of the 50-60s it can be assumed that emerging economies are on a trajectory of increasing TC. This means that a timely intervention in order to change the trajectory to a lower carbon one might avert a costly transition in the future.

3.1.3 Conclusion

The previous analysis has shown that the German electricity sector faces high structural and capital TC form high to low carbon technologies. However the data indicates that the system has entered a phase of decreasing capital TC. This offers a window of opportunity for policy to foster a transition to an alternative socio-technical regime. Changes in regulation, public awareness and support infrastructure can help reduce the public and financial TC. How these results compare to the recent Energiewende will be discussed in the chapter 4. Technological TC can be reduced by means of deployment subsidies or R&D subsidies. A decisive factor between the two policies can be the extent of capital TC. Deployment subsidies are not effective or extremely expensive if the existing capital TC are high. R&D subsidies on the other hand can be effective regardless of the existing asset base. Thus one should focus on R&D subsidies until switching assets can be achieved at reasonable cost. This underlines once again the importance of policy timing.

3.2 Policy Comparison: Risk of Creating Future Transition Costs

The previous analysis has shown that there are significant TC from high to low carbon technologies in western electricity sectors. Based on this finding the last section suggested several options for policy intervention. A precondition for identifying the best policy tool is a decision on the desirable state the system should transition to. In this regard the transition from high to low carbon electricity technologies represents a special case. While there are many low carbon electricity generation technologies available, most of them are still developing rapidly whereas others are still in early innovation stages. Thus, there is a high uncertainty about the desirable future electricity generation mix. Consequently, if a government has the intention to intervene at the current stage, it ought to evaluate the possible policy options regarding their risk of creating future TC. For example, a policy tool that is very efficient in fostering change to photovoltaic electricity generation might lead to high TC for all other low carbon generation technologies. In the long run, such a solution could lead to exit regrets, as previously discussed. Therefore this section will compare the risks of creating future TC for two major policy tools, namely deployment subsidies in the form of feed-in-tariff and public research and development spending. The analysis of each policy is structured along the previously defined framework of structural and cyclical TC. Thus it also provides an example how the framework can be applied for forward-looking analysis.

3.2.1 Deployment Subsidies

The following paragraph will analyze the impact deployment subsides have on creating TC, based on the example of feed-in-tariff (FIT). FIT is the fixed price a supplier receives for the generation of electricity from low-carbon sources. Thus it shifts the supply curve for electricity downwards, which decreases prices and increases quantity, as shown in figure 14. The demand curve is illustrated as being perfectly elastic at the retail price for electricity. This is based on two assumptions. First, initially low-carbon generation will supply a minor share of the total electricity demand. Secondly, the generated low-carbon electricity will always be given priority over other sources, as its margin costs are zero. Consequently the FIT increases the deployment of low-carbon technologies. It will be argued that FITs bear the risk of fostering all four categories of TC. At the center of the argument is the notion that FIT for low-carbon technologies does not benefit all possible technologies to the same extent. It is argued that only those technologies benefit which are close enough to commercial viability for the subsidy to shift the supply curve far enough downwards. Therefore, the policy timing and the tariff determine which technologies will be

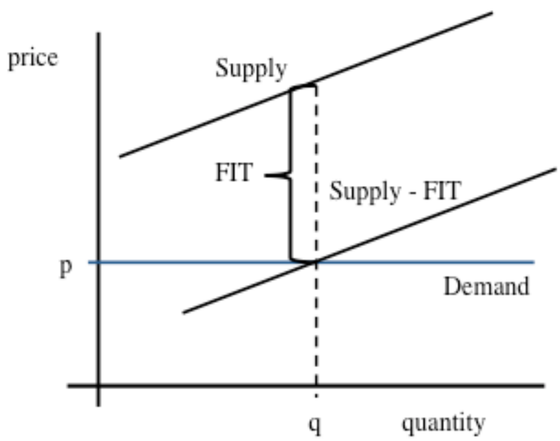

Figure 14 - Illustration of Effect of FIT; Source: Created by Author

deployed. Using Germany's FIT policy as an example, one can observe that although a wide range of technologies are eligible for FIT (several technologies in the area of Solar, Wind, Geothermal, Hydro and Biomass) 90% of subsidies are captured by only three technologies, namely wind turbines and silicon based PV and biomass (Bundesnetzagentur 2010). As these technologies become deployed more than others, they are increasingly subject to scale and partially learning effects, which creates TC to other electricity technologies.

In the following paragraph the impact of FIT on each category of TC will be discussed, using existing literature and examples of the German FIT system. Structural TC will be discussed first, followed by capital TC. Figure 15 shows the reinforcing dynamics between FIT and TC.

As previously shown technological TC can arise from continuous investment streams in one technology yielding learning and scale effects. In this regard, Nemet (2006) published a study on the different drivers behind the cost reduction in PV. He found that approximately 18.5% of the cost reduction between 1975 and 2001 is purely driven by deployment scale. In addition, 25.7% can be attributed to efficiency-increase effects, which he uses as a proxy for learning effects. The remaining 50% are largely a decrease in input costs, which is partially driven by a more mature support sector. The PV supply sector developed relatively quickly due to the technological proximity to the computer chip supply industry. However a decrease in input costs can also be a sign of standardized contract and therefore lower legal cost. As shown in figure 15, depending on the specific design of the policy, there can be a reinforcing mechanism between technological TC and FIT. For instance, the German FIT policy is designed to fade out subsidies as the technology becomes commercially viable. The

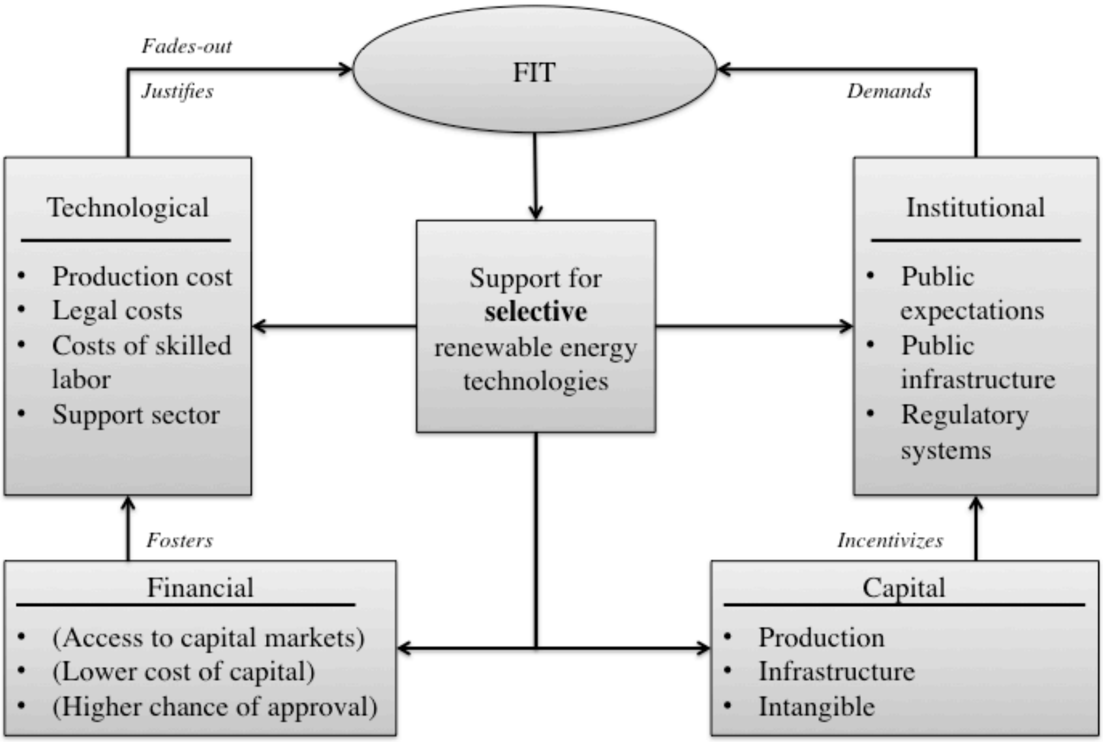

Figure 15 - Effect of FIT on TC; Source: Created by Author

fade-out scheme is defined by groups of technologies. Subsidies are being reduced depending on the installed low-carbon electricity generation capacity. As certain technologies benefit early on from FIT and are thus being deployed more, subsidies will be reduced, which consequently decreases the funding for other technologies of the same group. This means that while silicon based PV modules become cheaper the financial support for other solar technologies is being reduced, creating even higher TC.

Another mechanism through which FIT drives TC is the high demand for new support infrastructure, such as electricity grid expansion, resulting from the deployment of low-carbon technologies. The grid expansion in Germany is mainly undertaken by the private sector but partially subsidized by the government. Therefore it impacts technological as well as public TC. Over less than a decade 5.8 billion Euro will be invested for the expansion of the German grid to connect wind-power generated in the North Sea (Stern 2013). To put this investment into proportion, RWE Innogy, is currently investing 1 billion Euros in to the flagship North Sea wind farm. Thus, the considerable investment into the grid expansion creates long-term incentives to deploy further wind energy in this region, which is deepening the technological as well as public TC. The main contribution to public TC resulting from this investment is the strong signal of commitment the government sends that certain technologies will be supported. This is also true for the FIT itself, as they are usually fixed for several years in to the future (20 years for Germany). However a detailed analysis of the effects of public TC based on investments in adaptive expectations are beyond the scope of this paper and require further studies in the future.

Additional public TC can arise from the co-evolution of public and private institutions with the technology building socio-technical regimes, as previously argued (Unruh, 2000; Geels, 2012). Governmental institutions evolve in order to monitor and regulate the distribution of subsidies. When a subsidized technology emerges as the dominant design the governmental institution might become increasingly specialized as well. In addition to governmental institutions there are private institutions that co-evolve with the creation of an industry and thus spur indirectly from deployment subsidies. A dominant type of those private institutions is lobbying associations. A study of the Konrad Adenauer Stiftung (2009) found that Germany has one of the most influential renewable energy lobbying groups worldwide, namely the Bundesverband-Erneuerbare-Energien. The aim of this association is to increase the support for their technology or industry, which increases the pressure for a selective focus of deployment subsidies. Further studies are certainly necessary to improve our understanding on the co-evolution of technologies and institutions.

Financial TC arise when established technologies have cheaper and faster access to capital than new ones. While FIT policy does not directly impact access to capital markets nor provide investment capital, it does send a reliable long-term signal to investors. Such signaling decreases uncertainty and can thereby reduce cost of capital and speed up access to capital markets. However, this theoretical argument is not supported by the Gallagher et al. (2012) findings that governments and VCs finance most renewable energy projects. One possible explanation is that the governmental signal is not reliable enough for the market. Since the Spanish government retrospectively changed the FIT for solar the capital market might not react as strongly to the signal as otherwise would be expected. In addition, the credit crunch of the financial crisis since 2008 might have increased the barriers to access conventional financial markets. Further studies are required to investigate the contradicting arguments.

The previous paragraphs have presented examples and studies indicating the link between FIT and increased structural TC. The following discussion will focus on the impact of FIT on capital TC.

As discussed, capital TC arise expectations about future benefits over the lifetime of an asset. In this context one can differentiate between three main categories of assets: production capital, infrastructure and intangible capital. As described before the FIT is mainly captured by three technologies wind, silicon based PV and biomass. Wind and solar are in particular decentralized and location dependent. This creates the necessity for large-scale grid expansion. Referring back to the previous example, the connection of a wind farm in the North Sea to the German grid is expected to require investments of 5.8 billion Euros. These investments have been undertaken based on the expectation of a certain amount of electricity being transmitted over its lifetime. If there are no future investments in North Sea wind parks or the technology were to become obsolete in general, the companies would lose significant future cash flows. The same argument is true for investments in production capital for manufacturing the low-carbon electricity technologies as well as the generation plants themselves. The asset lifetime of, for example, PV modules is about 20 years. Therefore a switch away from PV would lead to a loss of expected cash flows over the coming two decades. In addition to the direct impact on capital TC, deployment increases the incentive for lobbying, as a policy change or new technology could reduce the return on the illiquid assets.

This section has presented some initial arguments for the link between FIT and TC. At the center of the analysis is the notion that FIT does not provide the same opportunity for each of the competing technologies. Therefore, governments are effectively picking winners by implementing FIT. It has been argued that there is a risk of creating high TC to the many technologies that are still in relatively early innovation stages, which consequently could lead to exit regrets.

3.2.2 Research and Development Subsidies

The following sub-section will present arguments and studies on the link between public R&D spending for electricity technologies and future TC. It will be shown that this policy tool bears a low risk of creating future TC. The main reasons for this are the absence of any investment in scale as well as a lack of investment in tangible assets, which would create expected future benefits. The analysis is structured along the four types of TC, starting with the structural TC.

The first question that needs to be answered is whether R&D subsidies crowd-in or crowd-out private R&D spending. If public spending were a perfect substitute for private R&D spending, then the policy would not create any additional TC above those that were created anyway, regardless of the connection between R&D spending and TC. The literature on crowd-in/out effects is well-developed but inconclusive on that matter. David et al. (2000) compared 33 papers and found that 11 of them showed significant substitution effects, 18 reported public spending being complementary and four were without significant findings. Most of the data has stemmed from the US and is only different in level of aggregation as well as industry focus. While there is no consensus about the overall effect Nemet and Kammen (2005) conclude that the evidence for crowd-out effects of large-scale public R&D projects is "weak or non-existing" (Kammen & Nemet 2005). This is relevant as energy R&D programs are usually long-term and large-scale. In the most recent publication Popp & Newell (2012) analyze crowd-out effects of public energy research projects in the US. The regression based on patent data shows that an increase in public energy R&D spending does not decrease patent activity in other industries. In conclusion previous research has not been able to provide a clear answer to the question of whether public research subsidies are a complement or a substitute to private spending. The lack of more granular data and the heterogeneity of R&D projects does not allow for a definitive conclusion on this matter, however for the purpose of this analysis it will be assumed that public R&D spending is a perfect complement to private spending.

The first category to be discussed is technological TC. As public R&D funds have no direct link to mass production there are no investments into scale. Yet, the funds, when successfully deployed, result in learning effects. When analyzing whether these learning effects lead to technological TC one has to consider the mechanisms governing the allocation of funds. If funds were to be allocated over a wide variety of R&D projects on varying technologies, one could argue that the simultaneously occurring learning effects do not foster significant TC. However, if governments limit funding to only certain technologies or focus on those with short-term gains then these technologies are more likely to evolve as the dominant design. This would result in picking winners analogous to the effects of FIT. In this context one has to differentiate between technology specific R&D and basic R&D. First the case of technology specific R&D will be discussed. Braun (2003) has argued that governments can either allocate funds by *blind delegation* or through *delegation by incentive*. The latter mechanism aims at setting price signals in order to steer R&D activities. Similar to deployment subsidies this funding method is likely to benefit technologies that demonstrate short-term results, which increases the chance of technological TC. Blind delegation circumvents the selection issues by funding institutions which in turn allocate the funds internally. As Polanyi (1962) has argued the scientific community is reactive to publications signals, meaning that an area with a lot of publications is more likely to receive additional funding in the future. Therefore, even under blind delegation it is likely that an established technology will receive the lion's share of the funding. Based on this reasoning it can be concluded that technology specific R&D subsidies are likely to be spent on a narrow selection of technologies, which fosters TC. Yet this is not the case for basic research; this research will benefit a wide variety of technologies. This is one of the main reasons why under Carter the United States had focused their public R&D spending almost exclusively on basic scientific research. However, it has been argued that this policy led to an underinvestment of R&D in many areas and was therefore later amended (Feinmark 1982). Figure 16 shows the feedback loop between TC and subsidies. As

R&D subsidies reduce costs of a certain technology, further spending on this technology is being justified. However the more mature the technology becomes the more likely is also a fade-out of the subsidy program, comparable to the dynamic of FIT fade-outs. Furthermore, successful development programs can foster public expectation, creating public TC. The discussion has provided initial evidence for public R&D spending fostering TC through investments in learning. However this link is weaker than the one with FIT due to the lack of scale investments. The next paragraph will discuss the link to public TC. Committing public funds for R&D on low-carbon electricity technologies can act as a signal to the public and the market for long-term support of these technologies. If funds are allocated to only certain technologies, this can foster adaptive expectation, which in turn speeds up the development of these technologies and creates TC to others. However, as previously argued studies have not found a strong crowd-in effect that would support the adaptive expectation argument. The following two reasons could explain these findings. First, R&D can potentially have long time lags, which might also slow down public adaptation. Secondly, crowd effects might simply not be the right indication for adaptive expectations among the public and the market. Future studies should for example look at the impact on public perception or market-pull effects. Besides adaptive expectations, public TC can arise from R&D networks and increased lobbying. Higher R&D funds can lead to stronger ties between research institutes, which might increase their lobbying power. Analogous to the lobbying arising from FIT, this will likely further narrow the selection of technologies benefitting from the subsidies. It can be concluded that there are indications for a link between R&D subsidies and public TC, however the signal is likely to be weaker than the one created by deployment subsidies.

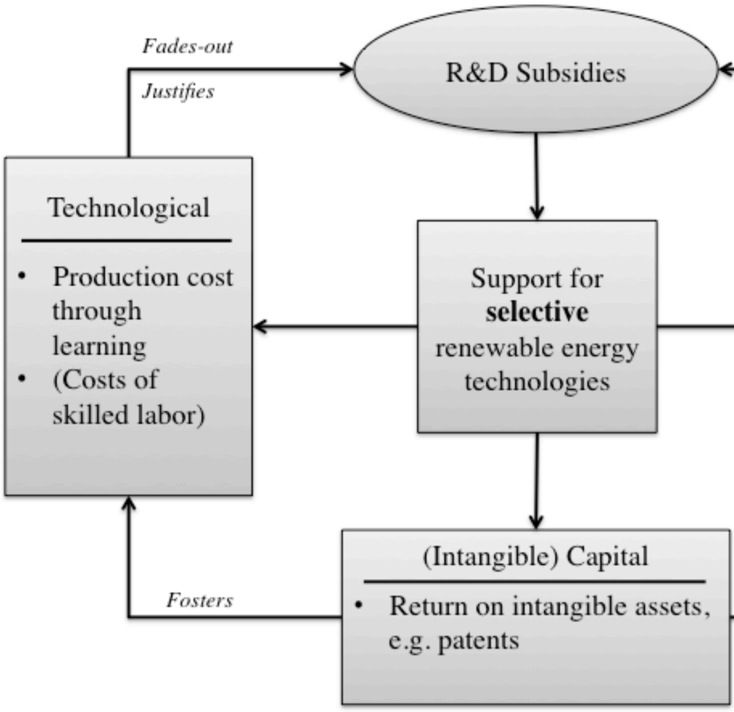

Figure 16 - Effect of R&D Subsidies on TC; Source: Created by Author

There is no link between R&D subsidies and financial TC because the subsidies do not create additional financing demand. This is based on two arguments. First, over time the policy shifts the supply curve downwards; however unlike deployment subsidies it does not immediately create an artificial demand for the technology. Secondly, there is no crowd-in effect attached to the R&D subsidies; thus, no additional demand for R&D project financing is triggered by the policy.

Based on the same arguments the policy does not create expectation of future benefits from tangible assets. However, the R&D processes create intangible assets, such as patents, which in turn create expectations of future payoffs. An analysis on the return on intangible assets is out of the scope of this thesis; however, as deployment subsidies lead to tangible and intangible assets the policy is likely to lead to higher capital TC than R&D subsidies. Figure 16 shows how intangible assets can foster public expectation and in the form of learning effects increases cost difference between goods or systems.

This section offered some initial arguments and studies on the risk of R&D subsidies creating future TC. It has been shown that although the policy does foster the creation of certain TC, the link is likely to be weaker than policies aiming at direct deployment of the technology.

3.2.3 Conclusion

The previous analysis was aimed at providing insight on two matters. First, it offered an example of how to apply the analytical framework presented in the early chapter. Secondly, it offered some initial evidence for R&D subsidies bearing less risk of creating future TC. This is particularly important for policy making in the electricity sector where the desired future generation mix is still uncertain. In connection to the previous findings on the existing TC one can preliminarily conclude that high R&D subsidy policies might be more effective in reducing the structural TC in the near term. If necessary it is more efficient to complement this with a deployment subsidy at a later stage.

4 Conclusion

This thesis presented a new heuristic framework for transition of socio-technical regimes based on the idea of TC. It has been shown how the concept of TC can improve our analysis of the resilience of such regimes. The investigation of drivers for TC concluded that they are mainly created by investment paths, showing scale to adaptation, and expected future benefits from capital stock, as well as inter- and intra-spillover effects.

The theory has revealed three main issues for policy makers attempting to foster change: 1) Policy timing is of utmost importance for systems with a large proportion of LLKS. TC analysis can improve policy timing and consequently the effectiveness and efficiency of policy making. 2) The interconnectedness of elements within a socio-technical regime reinforces the system's resilience. Policy packages should therefore combine tools aimed at different elements of the regime, rather than focusing on just one. 3) Policies aiming to overcome TC have the potential to create future TC. Policy makers should give more consideration to this effect in order to prevent high costs in the future.

The application of the framework to the German electricity sector, as a case study for a carbon-intensive western system, has produced three important insights: 1) TC from a high to a low-carbon electricity system are likely to be significant enough to sustain the system beyond its natural cycle. 2) Ageing capital stock and increased environmental awareness is currently opening a window of opportunity for policy to foster a transition to a new regime; however due to the prevalence of LLKS in the system capital TC are still high compared to system dominated by SLKS. 3)

Structural TC remain high due, in particular, the supply side managed nature of the system, public norms and expectations, and the lobbing power of existing players.

4.1 Consequences for Policies

The previous paragraph summarized the main findings of the thesis. This raises the question of the consequences for energy policy. The following section will connect the findings to actual policy recommendations.

Technological TC from high to low-carbon electricity technologies have come down, over the last few decades, driven by high subsidies around the world as well as a significant reduction of input costs, caused by the shift of silicon supplier from the computer chip industry to the PV industry. These are both trends that are unlikely to sustain momentum. The current wave of consolidations and bankruptcies in the industry, as a result of oversupply and the reduction of FITs, will increase pressure on prices to rise again. In addition deployment policies have proven to be expensive, especially considering that other countries might capture much of the economic benefits. It is not enough for governments to trust in a constant decline in technological TC to result in change.

In light of these developments governments have to write policy packages, which simultaneously address multiple transition costs. R&D subsidies support sustained reduction in technological transition costs and at the same time provide information about the desirable electricity mix for the future. Furthermore, as argued in the last section, there is increasing evidence that this policy is less expensive and less likely to create future TC as it avoids picking winners and build up of capital stock. This policy has to be complemented by smart long-term investment programs in supportive infrastructure as well as well as policies addressing existing norms and standards. As a whole the policy package has to send a strong long-term signal, conveying one vision. This can help to bring financial TC down and reduced uncertainties for consumers.

Compared to the existing Energiewende the main differences are three fold: 1) One of the main pillars of the Energiewende is a high deployment subsidy as opposed to R&D subsidies. This policy is very expensive, does not consider the extent of LLKS in the system and creates future TC. 2) The Energiewende focuses on to few of the many elements sustaining this regime. For example, barriers to finance and involvement of large industrial players are under- or not represented in the policy. 3) The technology implementation focus of the Energiewende creates high uncertainties, as engineers and politicians still cannot sufficiently explain how an electricity system based on 80% or even 100% renewable energy is supposed to function.

Transition cost theory as presented in this paper can help decision makers to better understand the drivers of the resilience of socio-technical regimes. In addition, its application can be used to analyze the impact of policies on future transition costs. It thereby has the potential to improve policy making as well as policy timing. This is important in order to manage the necessary transition from high to low-carbon regimes as exemplified for the electricity sector.

4.2 Limitation and Future Research

Three main areas of limitation and future research will be discussed in this section, namely, lack of empiricism, generalizability, and consideration of welfare effects.

The framework and theory presented in this thesis are based on deductive reasoning, complemented by empirical evidence from previous authors. Until future research has tested and complemented this work with empirical findings, three major limitations should be kept in mind. First, figure 6 shows the mechanisms leading to TC. Without an empirical study the relative importance of each of the sources of TC is highly uncertain. Yet, this potentially has a significant influence on policy making, as spillover effects require different tools than direct investment paths. Secondly, as discussed in section 2.2 the list of TC ought to be scrutinized using empirical evidence. Finally, section 3 presented several possible categorizations of transition costs in order to derive the most suitable arrangement for policy analysis. To improve the robustness of the framework, the arrangement should be based on expert elicitations. It is anticipated that future empirical studies would both complement and scrutinize the presented theory.

The second area of limitation is the generalizability of the mechanisms and frameworks presented here. It has been stated that the theory applies to socio-technical regimes. Advancing technology is constantly increasing the range of what can be considered a socio-technical regime, from gas turbines to online social networks. The differences in dominance and combination of elements between two regimes might reach a point where only certain elements of the framework are relevant for one type, at this point one could not generalize the theory to all regimes. Future research should investigate how the framework fits different kinds of regimes. Another area of limited generalizability stems from the application section. The analysis focused in most parts on Germany as a case study for a mature, carbon-intensive electricity sector. However, as TC can be driven by specific industry and institutional structures further research is necessary to ensure generalizability of the results. In addition capital TC can vary significantly even between countries with similar systems. This is especially likely when comparing western countries, which suffered significant destruction during WW2 compared with those that did not.

Finally this thesis has focused on analyzing how TC are created and in turn limit the development of a regime to a certain path of incremental developments. The premise of the subsequent application was that such TC should be overcome. However, as briefly mentioned in section 1.3 TC are not necessarily welfare destroying and should not be overcome at any cost. Future research should complement the work presented here by investigating the effect of TC on welfare and investigate the question of long-term welfare effects when fostering radical transition compared to incremental developments.

Besides those limitation there are in general two areas for future research: studies focusing on scrutinizing the theory and other focusing on applying it. The most important questions concerning the first group are related to empirical evidence and have been mentioned above. In terms of application, future research should conduct a comparative case study between electricity systems in various countries. This would shed light on the question of how different structures among the players impact the strength of the feedback mechanisms. Furthermore, it could improve our understanding on where intervention by international institutions and investors would be most effective. Another worthy future endeavor is applying these frameworks to decisions in the private sector rather than the public sector. As discussed before, firms often face high transition costs to another good or service. Integrating these frameworks in managerial decision-making could help to reduce future TC and thereby decrease risk.

In conclusion much future research is necessary to test and potentially improve this framework. As a policy analysis framework it should not only be tested by academics but also by policy makers in order to improve policy making and to receive feedback on its applicability.

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Appendix A – List of Barriers to Energy Markets

IEA (2005) List of Barriers to Energy Markets

Table 4.1. Types of Market Barriers and Measures that can Alleviate them

Barrier	Key Characteristics	Typical Measures
Uncompetitive market price	Scale economies and learning benefits have not yet been realised	• Learning investments • Additional technical development
Price distortion	Costs associated with incumbent technologies may not be included in their prices; incumbent technologies may be subsidised	• Regulation to internalise 'externalities' or remove subsidies • Special offsetting taxes or levies • Removal of subsidies
Information	Availability and nature of a product must be understood at the time of investment	• Standardisation • Labelling • Reliable independent information sources • Convenient & transparent calculation methods for decision making
Transactions costs	Costs of administering a decision to purchase and use equipment (overlaps with "Information" above)	
Buyer's risk	• Perception of risk may differ from actual risk (e.g., 'pay-back gap') • Difficulty in forecasting over an appropriate time period	• Demonstration • Routines to make life-cycle cost calculations easy
Finance	• Initial cost may be high threshold • Imperfections in market access to funds	• Third party financing options • Special funding • Adjust financial structure
Inefficient market organisation in relation to new technologies	• Incentives inappropriately split – owner/designer/user not the same. • Traditional business boundaries may be inappropriate • Established companies may have market power to guard their positions	• Restructure markets • Market liberalisation could force market participants to find new solutions
Excessive/ inefficient regulation	Regulation based on industry tradition laid down in standards and codes not in pace with development	• Regulatory reform • Performance based regulation
Capital Stock Turnover Rates	Sunk costs, tax rules that require long depreciation & inertia	• Adjust tax rules • Capital subsidies
Technology-specific barriers	Often related to existing infrastructures in regard to hardware and the institutional skill to handle it	• Focus on system aspects in use of technology • Connect measures to other important business issues (productivity, environment)