Development of an Architecture Framework for Portfolios of Sustainable Technology Projects

By Kimberly Davis

BS in Industrial Engineering, May 2001, Texas A&M University
MS in Industrial Engineering, May 2003, Texas A&M University
MBA, May 2006, Carnegie Mellon University

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Dissertation directed by

Shahram Sarkani
Professor of Engineering Management & Systems Engineering

Thomas A. Mazzuchi
Professor of Engineering Management & Systems Engineering
The School of Engineering and Applied Science of The George Washington University certifies that Kim Davis has passed the Final Examination for the degree of Doctor of Philosophy as of 22 August 2012. This is the final and approved form of the dissertation.

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Kimberly Davis

Dissertation Research Committee:

Shahram Sarkani, Professor of Engineering Management & Systems Engineering, Dissertation Director

Thomas Mazzuchi, Professor of Engineering Management & Systems Engineering, Dissertation Co-Director

Lile Murphree, Professor of Engineering Management & Systems Engineering

Thomas H. Holzer, Adjunct Professor of Engineering Management & Systems Engineering
Dedication

I dedicate this dissertation to my husband, Joseph Benjamin Davis, Jr.
Acknowledgements

I would like to thank everyone who has helped me through this process and contributed to this research. The following list is by no means exhaustive.

First and foremost I would like to thank my husband, Joseph, for his constant and unwavering support and encouragement. This process would have been unbearable without his confidence in me and his emotional and intellectual support during the bumps in the road. I can honestly say I couldn’t have done it without him. I would also like to thank the rest of my family for putting up with prolonged delays in returning phone calls, for inquiring (in a cheerful and supportive way) about my progress for the last few years and for humoring me by listening to extended explanations of progress and work remaining.

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Abstract

Development of an Architecture Framework for Portfolios of Sustainable Technology Projects

Achieving environmental sustainability is a significant challenge, with the development and diffusion of sustainable technologies widely regarded as a key component to achieving sustainability. The literature on diffusion of innovations, evolutionary economics, and Science and Technology Studies inform a recent body of literature around transitions to sustainable technologies. Key theories within this field of transitions to sustainable technologies are strategic niche management, multi-level perspective, and transition management. Common elements of these three theories includes concepts of niche, regime, and landscape, transition pathways, stakeholder networks, and challenges around knowledge retention and capture of lessons learned. The execution of multiple projects to identify, improve, and ultimately diffuse more sustainable technological solutions is also a common element of approaches to sustainable technology transitions. However, there is still a lack of tools for practitioners to support the planning, management and execution of such portfolios of sustainable technology projects.

The objective of this research is to develop a systems engineering approach, namely an architecture framework, which builds upon theories of transitions to sustainable technologies and supports management of portfolios of sustainable technology projects. The architecture framework’s use is demonstrated with real-world case studies and lessons learned are identified. Systems engineering is seen as an appropriate tool for dealing with issues of sustainability and the challenges associated with sustainable
technology transitions. Systems engineering has already been applied within the fields of sustainability, management of R&D portfolios, and, to some extent, technology transitions. Systems architecting, an approach from systems engineering, has been applied to information and defense systems, as well as to processes and complex socio-technical systems, and is used within this research to address the management of portfolios of sustainable technology projects.

Requirements derived from the sustainable technology transitions and systems architecting literature drove initial development of the architecture framework. Three cases studies were then identified and project portfolio information collected. Representative architecture descriptions were built based on the case studies and used to analyze and improve the architecture framework. Lessons learned from the case studies were used to refine and enhance the architecture framework construct. Potential architecture development processes were also developed. The resulting architecture framework meets the requirements driven by the literature, and was also seen to have practical utility based on the case studies. The architecture framework developed in this research provides a tool for the planning, management and execution of portfolios of sustainable technology projects. It also mitigates challenges around knowledge retention and capture of lessons learned. The integrated structure enhances knowledge sharing and evaluation of opportunities and challenges across the portfolio of projects.

Note: A shorter version of this work was accepted for publication as a journal article in Systems Engineering. (Davis, Mazzuchi, & Sarkani, 2013)
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List of Acronyms

ADM  Architecture Development Method
AF   Architecture Framework
ANSI American National Standards Institute
ANT  Actor-Network Theory
BRM  Business Reference Model
C²   Command and Control
C4ISR Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CLIOS Complex, Large Interconnected Open Socio-Technical
COIM CLIOS-OPM
DoD  Department of Defense
DoDAF Department of Defense Architecture Framework
DRM  Data Reference Model
EA   Enterprise Architecture
EAP  EA Planning
ES   Engineering Systems
FEA  Federal Enterprise Architecture
FEAF Federal Enterprise Architecture Framework
IDEF Integrated Definition
IEC  International Electrotechnical Commission
IEEE Institute of Electrical and Electronics Engineers
INCOSE International Council on Systems Engineering
ISA  Information Systems Architecture
ISO  International Standards Organization
IT   Information Technology
<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>LTS</td>
<td>Large Technical Systems</td>
</tr>
<tr>
<td>MLP</td>
<td>Multi-Level Perspective</td>
</tr>
<tr>
<td>MODAF</td>
<td>Ministry of Defence Architecture Framework</td>
</tr>
<tr>
<td>MS</td>
<td>Microsoft</td>
</tr>
<tr>
<td>NAF</td>
<td>NATO Architecture Framework</td>
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<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
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<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>NMP4</td>
<td>Dutch 4&lt;sup&gt;th&lt;/sup&gt; National Environmental Policy Plan</td>
</tr>
<tr>
<td>OMB</td>
<td>Office of Management and Budget</td>
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<td>OPM</td>
<td>Object Process Methodology</td>
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<td>PAF</td>
<td>Process Architecture Framework</td>
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<td>PRM</td>
<td>Performance Reference Model</td>
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<tr>
<td>R&amp;D</td>
<td>Research &amp; Development</td>
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<tr>
<td>RM-ODP</td>
<td>Reference Model for Open Distributed Processing</td>
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<td>ROI</td>
<td>Return on Investment</td>
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<td>SCOT</td>
<td>Social Construction of Technology</td>
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<tr>
<td>SCRM</td>
<td>Service Component Reference Model</td>
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<td>SE</td>
<td>Systems Engineering</td>
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<tr>
<td>SNM</td>
<td>Strategic Niche Management</td>
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<tr>
<td>STS</td>
<td>Science and Technology Studies</td>
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<tr>
<td>SWOT</td>
<td>Strengths, Weaknesses, Opportunities, and Threats</td>
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<td>TM</td>
<td>Transition Management</td>
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<tr>
<td>TOGAF</td>
<td>The Open Group Architecture Framework</td>
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<tr>
<td>TRM</td>
<td>Technical Reference Model</td>
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<tr>
<td>UK</td>
<td>United Kingdom</td>
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Glossary of Terms

Architecture – Architectures, or architecture descriptions, are a representation, via products or artifacts, of a system of interest in terms of structure and interfaces, as well as the purpose, behaviors, and constraints of the system, resulting from an architecting process which documents the structure and interfaces (both internal and external) of a system. (ISO/IEC/IEEE, 2011; Maier & Rechtin, 2009)

Architecture Framework – Architecture frameworks provide guidance and structure (standards) for the process of architecting and the development of architectures. (Maier & Rechtin, 2009)

Aspect – The term ‘aspect’ is used for the architecture framework developed within this research to denote a collection of one or more architectural views within the architecture framework which have a similar purpose and content. Aspects are used within the architecture framework construct developed here for clarity of discussion and overall representation of the architecture framework structure.

Niches – Niches are environments and applications which provide protection against market forces and selection environment pressures to allow for experimentation with new technologies. Niches include the technology being developed, as well as the stakeholders involved and their shared experiences. (Schot & Geels, 2008)

Socio-Technical Landscape – The socio-technical landscape provides the context, or external structure, within which niches and socio-technical regimes exist. The landscape consists of broad, slow-changing factors such as macro market, cultural, economic,
demographic and political conditions and trends which cannot be directly influenced by regime or niche processes. (Geels, 2002; Raven, 2007; Schot & Geels, 2008)

**Socio-Technical Regime** – Socio-technical regimes consist of the dominant technology and associated shared cognitive routines and beliefs, rules and regulations, social norms, market and user practices, basic science, institutions, industry structures, and other infrastructure, which accounts for the long-term dynamic stability of socio-technical systems in fulfilling major societal functions. (Geels, 2002; Schot & Geels, 2008)

**Socio-Technical Systems** – Socio-technical systems encompass technological systems embedded within and influenced by social systems, which combine to fulfill societal needs and functions. Socio-technical systems are comprised of technology, infrastructure, rules and regulations, institutions, markets, users, industry structures, and cultural elements. (Geels, 2002; Maier & Rechtin, 2009)

**Sustainable** – A system (product and/or process) is sustainable (i.e. has the property of sustainability) if it consumes environmental resources and produces waste in levels which can be accommodated within the regenerative capacity of the affected ecosystem, and still meets human and economic needs. Sustainable systems balance economic, social, and environmental impacts and improvements. (Fiksel, 2003; Huesemann, 2003; Kemp, Loorbach, & Rotmans, 2007)

**Sustainable Transitions** – Transitions which “include a normative aim” (Raven, 2007, p. 2390) to improve environmental performance and achieve more sustainable technological solutions.
**Transition** – Transitions, as defined for this research, are significant, long-term, large-scale changes in the fundamental technology(s) utilized to fulfill the needs of major sectors of the economy (transportation, agriculture, energy, etc.) Transitions represent a structural shift from one socio-technical regime to another, which encompasses technological, social, infrastructure, and institutional changes. (Geels, 2002; Kemp, 1994; Raven, 2007; Rotmans et al., 2000)

**View** – Architecture views provide different perspectives of the same system, such that information is presented in a way that is both consistent and relevant to different stakeholders. (Sage & Lynch, 1998)

**Viewpoint** - Viewpoints specify the structure and content for the development of views. (Maier & Rechtin, 2009)
Chapter 1 – Introduction

1.1 Research Problem

For several decades, issues of sustainability have drawn attention from researchers, industry, and government. In 1987, the World Commission on Environment and Development report (WCED, 1987) highlighted the concept of sustainable development as an approach to solving growing global environmental problems. Research into sustainability and sustainable energy solutions has continued to grow, with investments in energy-related research by US firms projected to reach $6.7 billion in 2012, up 23% from 2011. (Broge, 2012)

Despite significant interest and investment in identifying sustainable solutions, the problem of achieving sustainability continues to be elusive and requires further research. This is in part due to the interdisciplinary and complex nature of sustainability. Achieving sustainable development has many aspects, including the need to identify and modify social and economic behaviors such as changing patterns of consumption and political focus. (Kohler, 2006) There is also a strong technological component to addressing the issue of sustainability. Achieving environmentally sustainable technologies is widely regarded as a critical component, and even the primary approach, to achieving sustainable development. (Paredis, 2011)

With regard to introduction of sustainable technologies, several theories and approaches have emerged in recent years which focus on achieving large-scale shifts, or transitions, in the predominant technologies towards more sustainable solution sets. Within this body of literature on socio-technical system innovations and sustainability transitions, a key idea is the use of multiple projects, or experiments, to identify, improve,
and ultimately diffuse more sustainable technological solutions. Such portfolios of projects must be planned, executed, and monitored in a way that supports the overall objective of sustainability. (Geels, 2002; Rotmans, et al., 2000; Schot & Geels, 2008) The challenge then is in effectively identifying and managing multiple projects in such a way that leads to long-term sustainability, and in identifying the right tools for practitioners to use in this effort.

The goal of achieving sustainability requires an interdisciplinary approach, with an integrated systems perspective of the social, environmental, economic, and technology aspects of sustainability and processes of technological change. (Bakshi & Fiksel, 2003) There is recognition within the systems engineering literature of the importance of sustainability, the role of systems engineering in achieving sustainability, and in particular the potential effectiveness of systems engineering tools and methods for supporting processes towards enhanced environmental sustainability. (Levy, Hipel, & Kilgour, 1998) Systems engineering – viewed as an integrated approach to complex problems involving technologies, people, organizations, and environments – is well-suited to the challenges of identifying and implementing sustainable solutions. However, there still exists a lack of systems engineering tools which are specific to managing portfolios of sustainable technology projects and which match the theories of technology transitions to good systems engineering practices. This research addresses the problem of a lack of tools for practitioners to support planning, management and execution of portfolios of sustainable technology projects through the development of a formal architecture framework.
1.2 Research Overview

The objective of this research is to develop a systems engineering approach, namely an architecture framework, which supports management of portfolios of sustainable technology projects. A review of the relevant literature on technological innovation and diffusion, technology transitions, systems engineering applications, and architecting and architecture frameworks is provided. The architecture framework is developed to be consistent with the predominant sustainable technology transitions literature. Both the theoretical and practical need for such a framework will be illustrated.

As part of this research, case studies were conducted to analyze and improve the architecture framework. Case study data was utilized to develop representative architectures via the framework developed within this research. The final architecture framework, as refined through the case study process, and lessons learned from the case studies are presented and discussed in the context of the literature and research objectives.

1.3 Overview of Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 presents an overview of literature relevant to the problem and approach described above. A review of theories regarding innovation and technology diffusion is offered first, followed by a discussion of theories explicitly treating the problem of transitions to sustainable technologies. Key concepts and terms are defined within this discussion. Next, the field of systems engineering is introduced and relevant literature from the field is discussed. Key applications of systems engineering to the problems of sustainability, portfolio selection and management, and technology introduction and transition are reviewed.
Last, a detailed review and discussion of architectures and several architecture frameworks is presented.

Chapter 3 summarizes the literature presented in terms of the gap in research and applicability of the work undertaken in this research to both theory and practice. The motivation for this research is further discussed and illustrated with recent and relevant literature. Specific research objectives and questions are identified.

Chapter 4 describes the research methodology utilized in this study. A broad overview of the approach taken is described, followed by a detailed discussion of the case study process and the approach to initial development of an architecture framework. The questionnaire utilized in the case study is presented, along with a discussion of the characteristics of the cases themselves.

Chapter 5 further describes the structure, content, and evolution of the architecture framework, utilizing the information and lessons learned from the case studies. Detailed lessons learned are discussed and possible implementation approaches for the developed architecture framework are presented. A discussion of achievement of research objectives and responses to the research questions concludes Chapter 5.

Chapter 6 discusses conclusions and offers areas for further research.

Two appendices provide additional details regarding the architecture framework itself which were not included within the body of this dissertation for clarity of reading.
Chapter 2 – Literature Review

2.1 Technology and Innovation Theories

Numerous theories and schools of thought exist concerning innovation and the emergence, diffusion and widespread adoption of new technologies. A review of some of the major theories is discussed here. Geels (2004, 2005) also provides a good overview of the history of technology and innovation theories.

Rogers’ (2003) seminal works on diffusion of innovations focus on the mechanisms by which new ideas, technologies and processes are adopted and spread. With a focus on the diffusion process itself, he examines the role of price, performance, categories of adopters, change agents, mechanisms of diffusion, and market share (i.e. critical mass) and illustrates these concepts with numerous case studies. In addition to chronicling the history and key concepts of innovation diffusion research, Rogers also chronicles the growth of the field within the academic literature. One common and persistent concept throughout diffusion research is the S-shaped rate of adoption curve, shown in Figure 1 below. Geels (2005) discusses an extension to this model which describes the technology life cycle as occurring in three phases: birth and childhood, when the technology emerges, with low production volumes and market share but high uncertainty; adolescence, standardization occurs and competition increases around cost rather than innovation; maturity, markets are saturated and innovations become incremental, with a focus on economies of scale.
Evolutionary economics focuses firstly on the evolution of firms, with technology viewed as a contributing factor to a firm’s economic success. Dosi (1982), Nelson and Winter (1977) further studied the activities of engineers within firms, with particular respect to R&D functions, and found patterns in search heuristics which implied shared beliefs and routines within firms. These paradigms lead to long-term stability of firm activities. Firms may have different paradigms, leading to variation in new developments, or shared paradigms that can lead to a sector-level (meaning sectors of the economy such as transportation, energy, agriculture, etc.) technological paradigm, or technological regime. The concept of technological regimes is discussed further in the next section. Another branch of evolutionary economics is long-wave theory which focuses on large-scale changes in the economy-level technological paradigm (for example, the industrial revolution). Long-wave theory is concerned less with engineers’ cognitive activities and more with the processes of technological substitution where new technology replaces the old entrenched technology. Common themes emerge in historical case studies: new technology replaces the old, beginning in a few sectors of the
economy; new innovations are seen as resolving problems with the old technological
regime; diffusion occurs as a group of innovations begin to combine; structural changes
in the economy and infrastructure occur to accommodate the new innovation
(technological paradigm). (Freeman & Perez, 1988)

The field of Science and Technology Studies (STS) field offers additional theories on
technology introduction and technology lifecycles, of which three prominent theories fall
under the headings of Large Technical Systems (LTS) theory, Social Construction of
Technology (SCOT), and Actor-Network Theory (ANT). LTS describes the technology
life-cycle as having phases of invention, development, innovation, growth, competition
and consolidation, and momentum, guided by different types of system builders in
different stages. LTS introduced the term “seamless web” to denote the interrelationship
of technology, people and culture, organizations, institutions and environment within
LTS theory. This web is weak at first but gains strength and rigidity as the technology
life-cycle progresses. (Hughes, 1986, 1987; Mayntz & Hughes, 1988)

SCOT focuses on the socio-cognitive processes that enable the selection and
ultimately the stabilization of a technological regime. SCOT also utilizes the concept of
a technological frame consisting of goals, understanding of problems and solutions,
theories and methods, which emerges from social interactions and influences those
interactions and the development of the technology. A stable technology emerges when
the socio-cognitive processes (and associated social groups) converge on a common
understanding of the new technology. (Bijker, 1995; Kline & Pinch, 1996; Pinch &
Bijker, 1987) Similarly, ANT focuses on the development of socio-technical linkages to
support the development and emergence of a new technology into a working
configuration, as well as to enable the diffusion of technology. As more elements – consisting of people, skills, technologies, etc. – are linked together, the technological configuration stabilizes. As the network of elements grows, the technology further diffuses. (Callon, 1991; Latour, 1987, 1991)

While LTS, SCOT and ANT examine the introduction and acceptance of technologies, they are relatively silent on how those technologies then become susceptible to large-scale replacement. SCOT and ANT also focus primarily on technology emergence and stabilization with less attention paid to the diffusion process.

Complexity, or complex systems, theory emerged more than half a century ago, and has gained considerable attention in the past few decades as systems have grown increasingly large and complex, particularly with advances in computing systems. Complex systems exhibit many properties, including a multi-level structure, physical and non-physical elements, nested system properties, an inability to be adequately understood via a purely functional decomposition, high levels of interaction with their environment and unclear system boundaries, an evolutionary nature, and emergent behavior. The idea of emergent behavior is especially prominent in complex systems theory. (Abbott, 2006, 2007) Emergence occurs when a system exhibits behaviors at the system-level which are not immediately evident from examination of the elements that make up the system. The dynamic nature of complex systems drives a holistic, vice a reductionist, approach to understanding systems and their behaviors. (Beckerman, 2000)

2.2 Transitions to Sustainable Technology Theories

As society becomes ever more interested in reducing environmental degradation and increasing sustainable practices, technology is often regarded as an attractive solution to
such problems. (Kemp, 1994) While all new technologies face barriers to market entry, shifts to sustainable technologies face the additional challenges of (often) small-scale production, lack of institutional support from dominant energy firms, high costs of introduction versus uncertain benefits, uncertain market demand, and long development times. (Kemp, 1994; Kemp, Schot, & Hoogma, 1998) Other challenges to the widespread adoption of sustainable technologies include: sustainability as a weaker motivation than economics (Hoogma, Kemp, Schot, & Truffer, 2002); lock-in of the current regime through embedding in the current landscape and strong integration between the current technology and the associated infrastructure and user practices. (Caniels & Romijn, 2008)

A relatively new body of literature has emerged which is specifically concerned with transitions to technologies which are sustainable. Transitions are defined as significant, long-term, large-scale changes in the fundamental technology(s) utilized to fulfill the needs of major sectors of the economy, encompassing technological, social, infrastructure, and institutional changes. (Geels, 2002; Kemp, 1994; Raven, 2007; Rotmans, et al., 2000) Sustainable transitions then are transitions which “include a normative aim” (Raven, 2007, p. 2390) to improve environmental performance and achieve more sustainable technological solutions. The three significant bodies of work within this field of literature are strategic niche management (SNM), multi-level perspective (MLP), and transition management (TM). These theories and approaches have been recognized by scholars as important in that they focus on technology for sustainable development and for their incorporation of broader societal impacts into a socio-technical co-evolutionary perspective. (Paredis, 2011) Each of these theories is
explored in detail in the following sections, along with a discussion of research to-date within those fields. An overview of the current open research gaps and questions identified within these three bodies of literature is also discussed.

There are several common themes and language among these theories. One significant similarity is the concept of niche, regime, and landscape. Niches are environments and applications which provide protection against market forces and selection environment pressures to allow for experimentation with new technologies. Niches include the technology being developed, as well as the stakeholders involved and their shared experiences. (Schot & Geels, 2008) The landscape, often referred to as the socio-technical landscape, provides the context, or external structure, within which niches and regimes exist. The landscape consists of broad, slow-changing factors such as macro market, cultural, economic, demographic and political conditions and trends which cannot be directly influenced by regime or niche processes. (Geels, 2002; Raven, 2007; Schot & Geels, 2008)

The concept of regimes, or socio-technical regimes, has evolved within the literature for several decades. The idea of a technological regime was used first by Nelson and Winter (1977) to describe the boundaries within which technologists search for technological solutions based on beliefs about what is feasible or reasonable. Georghiou et al. (1986) expanded this concept to include the notion of a “set of design parameters” which will define the general design and a shared “framework of knowledge” (Georghiou, et al., 1986, p. 32) within an industry. Dosi, working in the field of economics of technology, defined a similar concept of technological paradigm. The
technological paradigm not only influences the solutions explored, but also the search patterns of technologists and how the problem to be solved is itself defined. (Dosi, 1982)

The concepts of technological regime and paradigm have since been expanded to include more than just the cognitive activities of engineers, but also the broader technological, social, industrial and economic environment. Thus a technological regime is defined as “the whole complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology” (Kemp, et al., 1998, p. 182) thereby guiding the research and development activities of an industry, market forces, user practices, and government policy-making.

Dominant technological regimes benefit from what Kemp calls “dynamic scale and learning effects” (Kemp, 1994, p. 1027) where the technology design, manufacturing and distribution technologies and processes, related industries, complementary technologies, and other network externalities have the opportunity to improve and interact with each other, including the benefits associated with learning curve effects on costs.

Belt and Rip (1987) illustrated the sociological extension of the technological paradigm model by examination of a historical case study – the synthetic dye industry in Germany. Their study provides an example of the emergence of a technological paradigm that exhibited an exemplary product and process as well as a cultural matrix which sustains expectations of the success of the new technology. The public revelation of details of the new product and process for synthetic dyes and dyeing expanded the network of individuals who were aware of, understood, and believed in the value of the
new product and process, thus creating a social structure supporting the use and expansion of the new technologies.

Building on this historical evolution as well as later work in the field of sustainable technology transitions, recent literature defines the concept of socio-technical regimes as consisting of the dominant technology and associated shared cognitive routines and beliefs, rules and regulations, social norms, market and user practices, basic science, institutions, industry structures, and other infrastructure, which accounts for the long-term dynamic stability of socio-technical systems in fulfilling major societal functions. (Geels, 2002; Schot & Geels, 2008)

To illustrate the socio-technical regime concept, consider the example of the modern personal automobile with an internal combustion engine running on fossil-fuel based gasoline. There is a common grouping of technologies which make up the modern automobile and its engine. Further, there is a significant amount of infrastructure in place – dealers, gas stations, repair stations, manufacturers – which produce and support this set of technologies. There is also commonality of skill sets around automobiles of this configuration – car repair and oil change facility personnel are very familiar with this group of technologies, as are modern drivers, driving school instructors, and so on. Industry groups and government policies are also well established. The existence of this network of supporting infrastructure, skills and understanding, and institutions makes the technological regime of the personal automobile with an internal combustion engine fairly stable and difficult to significantly change or morph to an entirely new set of technologies.
To describe the patterns or evolutions of technological change, the concept of a trajectory or pathway is commonly employed. Two general categories of transition pathways are niche accumulation and hybridization (or technological add-on). Niche accumulation transitions involve new technologies which are significantly different from the existing regime (for example, pure electric automobiles vs. the internal combustion engine). These technologies are applied and matured in niches and eventually gain enough momentum to compete with, and eventually overtake, the dominant regime. In a hybridization transition, the new technology aligns with the existing regime (for example, hybrid automobiles which include an internal combustion engine), complementing current technologies in some way, eventually transforming the regime. In a hybridization pathway, the new technology does not have to directly compete with the dominant regime in the beginning. It is often not possible to prescribe a particular transition pathway in advance; rather the resultant pathway often evolves as the transition occurs. (Geels, 2002; Raven, 2007)

Other typologies have also been developed which distinguish more granular transition pathway typologies. Berkhout, Smith and Stirling (2004) posit four pathways based on availability of resources (internal vs. external) and level of coordination: reorientation; endogenous renewal; purposive transition; emergent transformation. Geels and Schot (2007) describe another typology of five pathways, distinguished by the timing and nature of interactions between the niche, regime, and landscape levels: reproduction (baseline state with no transition, regime is stable); transformation (regime modifies itself in response to landscape developments occurring when niches are not yet fully developed); de-alignment/re-alignment (unstable regime breaks up, multiple niche-
innovations compete for dominance with a new regime eventually converging);
technological substitution (regime destabilizes due to landscape pressures and mature
niche-innovations replace the old regime); reconfiguration (niche-innovations are adopted
by the regime and eventually transform it). These pathways can occur in a sequence as
well, one particular occurrence does not always tell the whole story of a transition.
Alkemade, et al. (2009) conducted a numerical simulation analysis of potential pathways
for personal transport systems which emphasized the importance of flexibility in
transition steps in order to achieve the desired end-state.

Technologies are subject to a selection environment in which they must compete.
The selection environment encompasses capital structures, physical infrastructure, supply
chains, production capability, technical skills, policies and regulations, user preferences
and social norms and is shaped by current (dominant) and historical technologies.
Historically, radically new technologies are often ill-suited for the current selection
environment and require time to become attractive to a wider audience. (Kemp, 1994;
Kemp, et al., 1998) Large scale changes in certain aspects of the selection environment,
such as regulations or infrastructure for example, may be required. Those technologies
which require fewer or less drastic changes in the selection environment will be adopted
more rapidly. Scholars believe that the current selection environment is being influenced
by environmental pressures, possibly (better) paving the way for more sustainable
technologies. (Tsoutsos & Stamboulis, 2005)

Kemp (1994) identifies conditions which are conducive to technological regime-shift
(or transition): new scientific discoveries; new needs which cannot be met with existing
technologies; current technological trajectories have reached a limit to their capabilities;
new entrants to an industry or market; willingness to accept risks; activities of non-market entities such as universities, research centers, or government procurement actions. Likewise, Kemp, Schot and Hoogma (1998) identify seven barriers to the adoption of new (sustainable) technologies: technological factors (immaturity, expense of new technologies); government policy and regulation; cultural and psychological factors; demand factors (volume of demand, alignment with specific consumer demands, and acceptable pricing); production factors (high cost of new production capabilities, sunk cost of existing production capabilities); infrastructure (high cost requires a critical mass); undesirable social and environmental effects (law of unintended consequences). Tsoutsos and Stamboulis (2005) added an eighth factor to this list: economic factors (the selection environment, “sailing ship” effects, high initial investment costs and high prices, low initial economies of scale and learning curves).

Kemp and Rotmans (2004) identify four policy areas which affect transition processes: science policy (innovation assessments, analysis of transitions); innovation policy (creation of alliances, research programs); sector policy (regulations, incentives, and barriers relevant to niches and specific innovations); control policy (economic policies which place pressure on the current regime).

While regimes are generally stable, or locked-in, through forces such as existing technologies, social networks, and institutional arrangements, this stability is dynamic. (Raven, 2007) Several approaches to modulating the dynamics of a regime have been developed which aim to effect a transition to new more sustainable technological regimes. These approaches are discussed next. The architecture framework developed in this research and presented later in this dissertation leverages the concepts from Strategic
Niche Management, the Multi-Level Perspective, and Transition Management as outlined in the following three sections.

2.2.1 Strategic Niche Management

Strategic niche management, born from technology studies, evolutionary economics, and literature on management of innovations, was developed specifically to address the management of innovations which are “socially desirable…serving long-term goals such as sustainability” and radical with respect to the existing regime (infrastructures, user practices, etc.). (Schot & Geels, 2008, p. 539)

The objectives of SNM are to:

- Determine the changes in the technology, social structure, and infrastructure which are required for the technology to be successful;
- Learn about the technical and economic feasibility and environmental desirability of the new technology;
- Further develop the new technology in terms of cost efficiencies, complementary technologies, and requisite skills;
- Build a stakeholder network behind the new technology. (Kemp, et al., 1998)

Caniels and Romijn (2008) and Schot and Geels (2008) provide good overviews and consolidation of the SNM literature. They describe SNM as an approach to facilitate the widespread adoption of new sustainable technologies through the use of protected spaces, or niches, ultimately resulting in transition of a socio-technical system. SNM promotes the use of niches to nurture new technologies and facilitate the co-evolution of
technologies with the associated infrastructures and user practices through the
involvement of a stakeholder network. Even still, the outcome of niche experiments and
the eventual niche formation is not pre-determined or directed. SNM is a process
management approach where the end goal is not fixed, but instead the process is managed
and oriented in a sustainable direction in a way which allows for experimentation and
learning. (Kemp, et al., 1998)

Under SNM, social and technological changes are intertwined and evolve together
through the use of niches to facilitate experiments with the new technology. As Kemp
(1994) points out those involved in developing and marketing a new technology need to
engage in shaping not only the technology, but also the market and technological regime
that will emerge around the new technology. The establishment of a niche is important
not only for the economic benefits and demonstration of technology viability, but also for
the learning effects and the building of a stakeholder network behind the technology.
Changes are also required in both supply and demand sides in order for new technologies
to successfully compete in markets. (Kemp, 1994; Kemp, et al., 1998)

SNM literature has converged on the identification of three processes internal to the
niche that are essential to the successful formation, development and expansion of niches.
The first is the expression and alignment of specific stakeholder expectations, society’s
needs, and the actual capabilities/benefits of the new technology. The second is learning
through experimentation. The value of the experiments lies in learning about the
technology’s benefits, limitations, means of use, cultural meaning, market/user
preferences, policy effects, and applicability. Third, the process of developing a
comprehensive actor network which works together to evaluate the technology and guide
the experimentation and niche formation. Broader and deeper networks are better, and it is important for the stakeholders to develop a shared view of the direction in which they and the technology are moving. (Caniels & Romijn, 2008; Schot & Geels, 2008)

Per Caniels’ and Romijn’s (2008) review of the SNM literature, strong conditions for the successful formation of niches include:

- Sheltered spaces for developing the new technology where the technology is not subject to market pressures and stakeholders are willing to accept initial inadequacies and associated high up-front costs;

- Ability to use and evaluate the new technology by multiple stakeholders while still immature, and preferably both within and outside of a laboratory setting;

- Conduciveness of the technology to learning from experiments and an ability to show improvement in the technology based on this learning;

- Openness – of both the technology and stakeholders – to developing the technology in various directions;

- Immediate attractiveness of the technology in at least one current setting. In other words, there should already exist at least one niche where the new technology’s benefits will override any current limitations or disadvantages.

Weaker conditions identified by Caniels and Romijn (2008) include: some level of instability in the current technological regime; stakeholder network characteristics including skill and knowledge levels as well as public and institutional support; interventions in the ongoing niche development process in the form of policies and
visioning. These weaker conditions are associated less with the technology itself, and more with the existing regime conditions, stakeholder actions and characteristics, and broader societal actions.

At a high-level, the SNM process involves socio-technical experiments where a collection of stakeholders engage in a learning process surrounding the new technology. The socio-technical experiment is conducted in a niche space, which initially is limited to a technological niche. Within this niche, or protected space, the technology is utilized in a narrow role and stakeholders learn about the new technology, its use, and potential market applications. Hopefully a market for the technology co-evolves along with the technological niche as market stakeholders become aware of and engaged with the new technology. If this co-construction of technology and market is successful, an actual market niche evolves and the new technology can be commercially successful outside of the niche. (Caniels & Romijn, 2008; Hoogma, et al., 2002)

SNM prescribes a five step process as outlined below. (Caniels & Romijn, 2008; Hoogma, et al., 2002; Kemp, et al., 1998)

Step 1: The Choice of Technology. The technology selected for the experiment should be environmentally or socially beneficial, open to adaptation, hold promise relative to stakeholders’ expectations and visions, be feasible with respect to user needs and practices, and already attractive for at least one application. (Kemp, et al., 1998)

Step 2: The Selection of an Experiment. The experiment should not represent such a significant leap that it is unachievable. The aim is to select an experiment
where learning and improvements can occur incrementally, in achievable steps. However, it is also important that the experiment be capable of producing tangible and meaningful results. Representative user involvement should be initiated at this stage. While this is the ideal structure for experiment selection, often the selection of an experiment occurs much more pragmatically, driven, for example, by commercial interests in the development of a new technology. Tsoutsos and Stamboulis (2005) argue that the identification of a concrete problem is essential, rather than deploying a technology in search of a need.

Step 3: The Set Up, Implementation of the Experiment. The focus of this stage is on learning processes and strengthening of the stakeholder network. While the change agent(s) drives the process, other stakeholders should be engaged in learning and adaptation activities and policy-makers in designing new policy strategies. Learning is aimed at both the technology (uses, adjustments and improvements, potential markets and users, problems and limitations) and the market (pressures, strategies), as well as the forces and interactions between the two. Another element of this stage is stakeholder management, where stakeholders interact with each other and the technology and co-develop, complemented by exercises to develop visions and scenarios. The stakeholder network should be dynamic, with membership and level of involvement changing over time. While the technology is to be protected in this phase, it should not be protected to the point where it is not forced to adapt to realistic market selection pressures.
Literature on the last two steps in the process is much more limited as few SNM experiments have reached this point. This limitation is further discussed below. For completeness, the last two steps are described here.

*Step 4: Scaling up the Experiment.* The experiment should be replicated elsewhere if possible, or tailored to meet other / further market needs in order to grow. One lesson from the infant industry literature is that experiments should be linked to complementary experiments within their value chain (i.e. suppliers, distributors, complementary technologies, associated processes).

*Step 5: Breakdown of Protection.* Protection should be removed if it becomes obvious that a technology will not be commercially successful. In this case, the energy of the stakeholder network should be redirected towards new experiments and technologies so as not to lose the momentum and learning from the experiment. On the opposite end, protection should also be removed if the technology is ready for market exposure.

SNM theory so far has primarily been used to analyze ongoing experiments with new sustainable technologies or past (non-managed) transitions. (For example, see (Brown, Vergragt, Green, & Berchicci, 2004; Harborne, Hendry, & Brown, 2007; Hegger, Vliet, & Vliet, 2007; Hendry, Harborne, & Brown, 2007; Ieromonachou, Potter, & Enoch, 2004; Kivisaari, Lovio, & Vayrynen, 2004; Truffer, Metzner, & Hoogma, 2004; Van Eijck & Romijn, 2008). (Schot & Geels, 2008) This limitation has caused some scholars to argue that SNM is useful as a research tool or a guide for managing experiments only,
and not useful as a real-world policy tool to affect large-scale socio-technical change (Caniels & Romijn, 2008).

In response to the divide between management of a single niche experiment and take-off of an actual market niche, Schot and Geels (2008) present an expansion of SNM theory which adds another dimension to the niche concept. In their conceptualization (see Figure 2), niches and associated niche experiments occur at both local (project) and global (niche) levels. In this way, experiments and niches are not conducted and developed in a singular manner; instead niches develop based on the experiences of aggregations of multiple experiments. The role and effect of learning is greater as experiments learn from and build upon each other. Project successes accumulate. Likewise, the concept of failure is more layered – while a local project may fail, the learning which takes place from this failure may help the global niche to develop and adapt further. The mechanism and actor(s) responsible for carrying lessons learned between projects varies and no formal tool or mechanism for conducting this process has yet been developed. (Schot & Geels, 2008).
SNM is intended to take new technologies from the early experimental phase all the way through to market niche development and ultimately regime change. However, current literature contains no strong examples of experiments explicitly conducted under the heading of SNM combining efforts and being carried forward ultimately to a regime change in the market. (Caniels & Romijn, 2008) While this is partly a reflection of the relative newness of the SNM literature and application, it also seems to indicate the need for new approaches, or at least supplementary tools, for effecting this transition. Scholars acknowledge the shortcomings of experiments in establishing viable niches which ultimately lead to regime change. Some concede that SNM is useful for demonstrating what is possible, but that other measures will be required to achieve a regime shift. (Kemp, et al., 1998)

Some open areas for research in the SNM arena include: identifying factors which cause sequences of experiments to result in successful niche development; management of portfolios of experiments to facilitate niche development; determining the appropriate amount of protection for a niche to develop; impact of visions on niche formation; how to
affect knowledge retention after completion of an experiment. (Kemp, et al., 1998; Schot & Geels, 2008)

2.2.2 Multi-Level Perspective

The Multi-Level Perspective (MLP) is not an approach to effecting technological transitions, but rather a framework for understanding and describing the dynamics of technological transitions. The MLP is built upon theories of evolutionary economics and sociology of technology. (Geels, 2002) MLP examines not just the bottom-up processes of niche development and expansion (as in SNM), but also the top-down effects of changes in landscapes and pressure on regimes. MLP combines the evolutionary and “process of unfolding” views from evolutionary economics, and also adds more focus on the selection environment and variations in this environment. (Geels, 2002)

MLP was originally developed to understand technological regime shifts, and posited the use of the three conceptual levels of niche, regime and landscape to understand these shifts. (Kemp, 1994; Kemp, et al., 1998; Schot, Hoogma, & Elzen, 1994) The MLP was further developed, tested, and refined using three historical case studies: the transition from sail ships to steam ships in British shipping; the transition from horse-drawn carriages to automobiles in America; the transition from piston to jet engines in American aviation. (Geels, 2005)

A key theme of the MLP is that technology is not stand-alone, it is embedded within a broader and social context which includes such elements as user and societal practices, policy and regulations, infrastructure, and natural resources. MLP incorporates all of the previously discussed concepts of technological regimes, technological trajectories, niche, regime, and landscape. These concepts are extended somewhat to define socio-technical
regimes and socio-technical landscapes where the concepts of regime and landscape are extended to include the rules and norms of the various social groups that are part of the socio-technical system. The concept of the socio-technical regime in MLP is defined as having seven dimensions: technology; user practices and markets; symbolic meaning of technology; infrastructure; industry structure; policy and regulations; techno-scientific knowledge. (Geels, 2002)

Within MLP, success of a technology is dependent not only on activities at the niche level, but also the ongoing dynamics at the regime and landscape levels. Effective niche development and management is still critical in that technologies need to be sufficiently exercised such that when the landscape and regime conditions are right the new niche (and eventually new regime) can be established. However, the niche is placed in the broader context of the regime and landscape. Socio-technical regimes account for stability in technological trajectories, but are subject to pressure from landscape changes and from niches. As the landscape and regime modulate, niche developments have an opportunity to expand and break through. In this way, the three levels of the MLP interact to account for processes of technology transitions. (Geels, 2002)

MLP literature converges on three interrelated processes which occur together to bring about transitions: learning processes and technical/economic improvements give momentum to ongoing niche-innovations; changes in the landscape create pressure on the dominant regime; regime dynamics destabilize creating opportunities for niches to break through. It is the accumulation of events and advances at the niche level which link up to apply pressure on the regime and even the landscape. The regime itself may evolve and reconfigure in response to the niche pressure as well as pressure from landscape changes.
In this way, regime shifts (technological transitions) are often gradual and difficult to predict or plan in advance. (Geels, 2002; Geels, 2005, 2007; Geels & Schot, 2007)

These processes are illustrated graphically in Figure 3 below. In the figure, the socio-technical landscape is seen at the top as a relatively stable structure with some ebbing and flowing of characteristics which can “push down” and affect the regime. In the middle of the figure is the socio-technical regime, consisting of the seven dimensions, which is fairly stable until the landscape creates pressure on the regime creating opportunities for niche advancements. At the niche level, numerous projects are ongoing and learning is taking place. If niche activities accumulate appropriately as the regime is experiencing pressure, the regime may be transformed by the niche technologies. In the end, whether through the advancement of niche technologies or some other reconfiguration of the dominant regime, a new socio-technical regime stabilizes along the seven dimensions.
Research into MLP is ongoing and not without its critics and as a result the research agenda into MLP remains active. Some areas of criticism, and for further research, include: more systematic case study research, specifically in the analysis of regimes; definition of transitions particularly in terms of beginning and end points; further distinction between radical transition and ongoing evolution of regimes; greater definition of various transition pathways; more emphasis on technology-social interactions and co-evolution and less technology-focus; the role of transition managers. (Genus & Coles, 2008)
2.2.3 Transition Management

Transition Management (TM) was initially developed for the Dutch 4th National Environmental Policy Plan (NMP4). (Rotmans, et al., 2000) TM utilizes principles from complex systems theory (Kemp, et al., 2007), has the MLP as a foundation, and also incorporates SNM. TM was described by its developers as “a deliberate, collective attempt to explore and bring about a transformation in a functional domain (such as energy supply or food production) in a gradual, forward-looking, and reflexive way, using a participatory approach.” (Rotmans, et al., 2000, p. 1) Kemp and Rotmans (2009) provide a detailed historical account of the development of the transition management framework.

The transition to new technologies under TM is envisioned as occurring in four phases (see Figure 4): pre-development; take-off; acceleration; stabilization. (Rotmans, Kemp, & Asselt, 2001; Rotmans, et al., 2000)

![Figure 4: Four Phases of Technology Transition (from Rotmans, Kemp & Asselt, 2001)]
**Pre-development phase:** The pre-development phase consists primarily of extensive experimentation and visioning. SNM is used to conduct strategic experiments in niches.

**Take-off phase:** Change begins and there is some evidence of a shift.

**Acceleration, or Breakthrough phase:** Significant structural changes are visible as socio-cultural, economic, ecological and institutional changes occur and interact. Learning processes take place, along with diffusion and embedding of the new regime.

**Stabilization phase:** The rate of change slows and a new dynamic equilibrium is reached. (Kemp & Rotmans, 2004; Rotmans, et al., 2000)

Like SNM, TM is not designed to identify and specifically manage towards a pre-defined end-state. TM is intended to guide efforts in a direction which is sustainable through an interactive process guided by shared collections of goals. These goals are not singular, but instead reflect various – flexible – options which meet the overarching goals of the transition effort. Goals evolve over time as necessary and are performance-related rather than solution-oriented. The transition is guided through the influence of both economic methods (incentives) and through planning and implementation of specific efforts (goals and experiments). Learning from events, and maintaining a variety of options and pathways throughout the process, are both critical elements of TM. Transitions both affect and are affected by economic, socio-cultural, and environmental conditions. (Kemp & Rotmans, 2004; Rotmans, et al., 2000) TM takes a complex
systems, systems thinking approach to governance for dealing with persistent societal problems. (Loorbach, 2010)

Transition management works in both a bottom-up – conducting experiments which contribute to learning and ongoing change processes – and top-down – establishing long-term goals, visions and policies and exploring numerous options – manner. (Kemp & Rotmans, 2004) Similar to SNM, TM is seen as a form of reflexive governance from a policy perspective (Vob, Smith, & Grin, 2009) and aims to integrate the policy approaches of incrementalism and planning to achieve success via “goal-oriented modulation” (Kemp, et al., 2007, p. 87) amidst co-evolutionary processes.

Seven properties of TM have been identified: long-term thinking to create short-term policy; thinking in terms of more than one domain and level; using long-term visions to establish short- and long-term goals; focus on learning; interactive, participatory decision-making; system innovation in addition to system improvement; maintaining a variety of options. (Kemp & Rotmans, 2004, 2009; Rotmans, et al., 2000)

The transition management approach has been described as a cyclical process with four stages, as depicted in Figure 5 below.
The first stage is the establishment of a transition arena, an idea unique to TM. The transition arena is an organization with innovative cross-domain members charged with discussing the problem at hand and formulating potential goals and transition pathways.

The second stage is the development of visions and agendas. Visions are long-term sustainability goals; while agendas are potential pathways to meet those goals. Agendas, specified as an actionable plan, translate long-term objectives into short-term actions, and are dynamic during the transition process.

The objective of the third stage is execution of the transition program, including creation and implementation of a portfolio of interrelated transition experiments which contribute to the overall specified sustainability goals. A portfolio of projects is necessary in order to maintain options and enhance learning processes. Experiments do not necessarily need to be successful economically, but should contribute to learning by
manufacturers, users, and policy makers in order to further the transition agenda. In this stage, the concepts of SNM are important in the selection and execution of experiments.

The final stage of the TM cycle is monitoring and evaluation of the transition process. Niche activities and developments, regime processes, the transition arena, transition goals and projects, barriers and opportunities, and learning processes are monitored and adjustments are made as necessary, continuing the TM cycle. (Kemp & Rotmans, 2004)

Thus TM occurs at three levels: the strategic level of visioning and goal formulation; the tactical level of agenda building and networking; the operational level of experimenting and implementing. Activities at these three levels are intended to interact under the TM framework to modulate the co-evolution of technological and social processes to move towards more sustainable solutions. (Kemp, et al., 2007; Loorbach, 2010) Similar to SNM, TM promotes the use of experiments. However, TM adds to the SNM approach by introducing the idea of creating visions and agendas, via transition arenas, before conducting experiments. (Schot & Geels, 2008)

Transition management has been used as a framework for analyzing/envisioning potential future transitions for transport and mobility (Kemp & Rotmans, 2004) and commercial aviation (Kivits, Charles, & Ryan, 2010). It has also been used to analyze past transitions such as the evolution of Dutch waste management (Kemp, et al., 2007). Bosch, Brezet and Vergragt (2005) used the TM concepts to develop an approach to identifying and initiating transition projects, with a focus on short- and medium-term projects which can be linked to long-term goals. Finally, through its adoption as formal policy in the Netherlands, TM has been purposively applied to transition projects for
regional development, industry transition (roofing), health care, and national waste management. (Loorbach & Rotmans, 2010)

Several lessons learned have been identified from the application of TM: every project is unique and the transition arena will develop differently based on the level of the project; identification and selection of arena participants is critical and should include both niche and regime participants; sufficient space and empowerment for thinking and experimentation is important; the existing regime will tend towards attempting to control the transition process; transition processes will evolve somewhat chaotically and should be guided in an organized but flexible manner; other results of the transition process include a new shared language, trust, and perspective; bridging the current situation to the future vision is a challenge but is aided by thinking in terms of TM concepts such as problem definition, visions, pathways, and experiments. (Loorbach & Rotmans, 2010)

Kern and Smith’s (2008) further analysis of Dutch energy transition policy utilizing TM revealed that energy transition efforts and policy remain separate from mainstream national energy policy and thus are having little effect on energy policy or re-framing primary energy issues. Further, market forces remain the dominant driver of technology solution, with social and environmental factors neglected in the market decision processes. Also the focus of efforts has been on the supply (or technological innovation) side and neglected demand-side changes and innovations.

Other challenges identified in the implementation of TM included control by incumbent regime actors, the need for short-term successes to maintain momentum, difficulties in maintaining a wide variety of options – in particular radically new options,
and practical (political) difficulty in implementing control policies to place pressure on the incumbent regime (change the landscape). (Kern & Smith, 2008) From a pure policy perspective, Vob, Smith and Grin (2009) identify challenges to TM which are common to long-term policy approaches: politics (democratic legitimacy and potential for capture by existing regime); context (institutional and implementation challenges); design as process (policy design is political and ongoing). Additional challenges to the TM process include practitioners struggling with transition terminology and administrative burdens, unbalanced power and fragmented projects (Avelino, 2009), and difficulties in translating the policy approach to new applications, particularly geographic locations (Heiskanen, Kivisaari, Lovio, & Mickwitz, 2009). Foxon, Reed and Stringer (2009) analyze TM and the adaptive management governance approach (typically applied to socio-ecological systems) and identified both similarities and opportunities for mutual improvement in these policy approaches. Of significance, adaptive management focuses on building resilience in systems, a focus which could be of benefit as well for problems where TM is applied.

The concepts of how technology transitions occur and the principles for managing projects to achieve technology transitions which are provided by the theories and approaches of SNM, MLP, and TM guided the structure and development of the architecture framework developed in this research. From these three theories, a set of requirements for an architecture framework to effectively manage portfolios of technology transition projects was developed and is presented in full in Section 4.1 of this dissertation. Some common and key elements of SNM, MLP and TM which are included
in this list of requirements include: capturing the features and dynamics of the relevant niche, regime and landscape levels associated with the portfolio of projects; monitoring of ongoing processes and changes in the niche, regime, stakeholder network, objectives, etc.; documenting both technical and social aspects of projects and ongoing processes; capturing current and future state; identifying stakeholders and stakeholder characteristics; providing short- and long-term goals and plans; assessing progress against barriers to technology transition.

The development of an architecture framework also addresses some of the identified gaps within the bodies of literature around SNM, MLP, and TM. Such gaps include practitioner difficulty with translating the theoretical approach into practice, knowledge retention and sharing of lessons learned between projects, and defined management approaches and tools for portfolios of projects. The relationship of this research, and the architecture framework developed within this research, to gaps within the literature is further explored in Chapter 3 of this dissertation.

2.3 Systems Engineering

Many definitions of systems engineering exist. Sage and Lynch state that systems engineering is “the profession associated with the engineering of systems of all types and with consideration given to all of the relevant issues that affect the resulting product or service, or process.” (Sage & Lynch, 1998, p. 178) They further conclude that systems engineers are concerned with people, processes, technologies, metrics, systems management, and environments. (Sage & Lynch, 1998, p. 179)

Levy, Hipel and Kilgour, in their argument for the application of systems engineering approaches to sustainable development, define systems engineering as “the professional
and academic discipline concerned with the analysis and design of large scale, complex systems at the interface of society, technology, and the environment.” (Levy, et al., 1998, p. 39)

The International Council on Systems Engineering (INCOSE) defines systems engineering as “an interdisciplinary approach and means to enable the realization of successful systems….SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.” (INCOSE, 2010, p. 6)

Sage and Rouse (1999) offer several definitions of systems engineering as well as a thorough discussion of the meaning, purpose and functions of systems engineering. Two of the definitions offered are systems engineering as “the management technology that controls a total system life-cycle process, which involves and which results in the definition, development, and deployment of a system that is of high quality, is trustworthy, and is cost-effective in meeting user needs” (Sage & Rouse, 1999, p. 3) and systems engineering as “management technology to assist and support policymaking, planning, decision making, and associated resource allocation or action deployment.” (Sage & Rouse, 1999, p. 5) They also identify numerous systems engineering methods and tools, including, but not limited to, engineering and project management, risk management, requirements management, configuration management, cost engineering, quality management, system architectures, systems design, systems integration, systems evaluation, functional analysis, analysis of alternatives, modeling, decision analysis, project planning, and knowledge management.
Key contributions of systems engineering to the management of projects, as summarized by Haskins (2007), include: understanding and management of requirements; risk and opportunity management; facilitating communications; providing a holistic perspective; process-orientation; dealing with complexity and change; stakeholder management and integration; providing unifying frameworks.

Through all of these definitions we see common elements of systems engineering as a multi-disciplinary, integrated approach to complex problems involving technologies, people, organizations, and environments. Systems engineering encompasses a broad scope of problem sets as well as a broad scope of methodologies and approaches for solving these problems.

Systems architecting is one of the functions of systems engineering, while architecture frameworks are a tool used by systems engineers and systems architects. Architectures are a tool for developing systems which integrate with other systems (products, processes, and organizations) and with human actors. (Sage & Lynch, 1998) The concepts of systems architecting and architecture frameworks are explored further in Section 2.4.

The remainder of Section 2.3 is devoted to the discussion of systems engineering as it has been applied to the problems presented in Section 1.1: sustainability, managing portfolios of technology projects, and introduction of sustainable technologies. A review of the literature on SE applications to sustainability, R&D portfolio management, and Transition Management is offered to show that, while there has been limited work directly integrating SE with sustainable technology transition efforts, SE research in
related and relevant areas (sustainability, portfolio management) is ongoing. In the case of R&D portfolio management, a significant body of literature exists and only a sampling of recent efforts is presented in order to illustrate the common focus areas within this field. R&D portfolio management is seen as a related and complimentary process to the architecture approach developed in this research. Explicit incorporation of R&D portfolio management and selection approaches into the architectural approach developed in this dissertation is left as an area for future research. Sustainability in general is emerging as a topic of high interest within systems engineering research, though SE work focused on theories of sustainable technology transitions has been limited to-date.

2.3.1 Applications to Sustainability

Haskins (2007) proposes a systems engineering framework for eco-industrial park formation. Eco-industrial parks are established to allow for cooperation between firms to minimize environmental impacts. Haskins’ framework utilizes systems engineering principles in the context of eco-industrial park projects to identify and coordinate stakeholders, frame the problem, evaluate alternatives, and implement a course of action which is monitored and revised as needed. Systems engineering, and systems engineers, are seen as the glue which holds this process together and provides for proper functioning of the process. This work thus provides a good illustration of the application of a systems engineering approach to complex sustainability-oriented problems and systems.

The work of Bakshi and Fiksel (2003) recognizes that sustainability involves the entire system and thus a rethinking of the boundaries of a system and associated processes beyond traditional physical and corporate boundaries. Specific challenges identified for process systems engineering in the context of achieving sustainability
include development of systematic frameworks, understanding theories of sustainable systems, identification of effective sustainability performance metrics, understanding the dynamics of industrial and ecological systems, and development of integrated models.

Fiksel (2003) further suggests that systems engineering approaches should be employed to design systems with resilience, where resilience is viewed as an inherent system property. He proposes that consideration of sustainability and system resilience be incorporated into the systems engineering functions of defining system boundaries and functions, requirements development, technology and design selection, system performance evaluation, and system deployment planning.

Ender, Murphy and Haynes (2010) developed a tool for the selection of an energy purchasing strategy which incorporates use of renewable energy systems. The resulting energy strategy is intended to balance renewable and non-renewable energy sources to meet load requirements and manage costs. Solutions are developed through a combination of systems engineering tools including modeling and simulation, design of experiments, and quality function deployment (QFD).

Kohler et al (Kohler et al., 2009) directly apply systems dynamics and agent-based modeling, combined with the theory of MLP, to simulate transition dynamics for the personal transport sector. Transport data from the UK as well as characteristics of possible changes in vehicle technology and personal behaviors were used to explore possible transition pathways via modeling and simulation. Their work demonstrated that lifestyle changes are necessary for a complete transition but are also more challenging to effect than technological change, and that preferred technology alternatives in the short-
term may be replaced in the long-term. Their work also illustrates that modeling and simulation techniques can be applied to the complex processes of technological change for sustainability.

Ranky (2010) provides a high-level overview and discussion of the various “green engineering” research topics to-date. Green engineering is recognized as a complex field requiring diverse, integrated perspectives. One of the key research opportunities identified within green engineering is the need for comprehensive frameworks and integrated architecture models for standing up and managing green programs.

2.3.2 Applications to R&D Portfolio Management and Project Selection

A significant body of literature has been written around systems engineering approaches to the selection and management of portfolios of projects, especially with regards to research and development (R&D) projects. Much of the work is focused on quantitative evaluation, optimization, and selection of projects at a firm-level. This body of work is focused on decision support approaches for the allocation of limited R&D budgets to an appropriate mix of projects to support overall firm and project portfolio objectives. A sampling of recent contributions to this field is discussed here to illustrate the general focus of this field within systems engineering.

Pereira and Veloso (2009) present an approach to selection of R&D projects based on evaluations of risk and return relative to overall objectives. Their approach involves evaluating constraints, evaluating risk and return, budget allocation, proposal evaluations, and overall portfolio selection with a quantitative evaluation process.
Martinez, Joshi and Lambert (2011) developed a qualitative goals evaluation approach to supplement existing quantitative optimization methods for portfolio selection. Their approach adds a path diagram methodology for the evaluation of non-quantifiable goals to the use of multi-objective combinatorial optimization for the evaluation of quantifiable goals.

Agresti and Harris (2009) present a profile-based selection approach tailored to selection of systems engineering R&D projects. Under their framework, projects are characterized as being targeting, reinforcing, enabling, or remodeling projects. Bitman and Sharif (2008) developed a ranking system for R&D projects which evaluates projects based on the factors of reasonableness, attractiveness, responsiveness, competitiveness and innovativeness. Chen, Ho and Kocaoglu (2009) present a strategic planning framework for building and evaluating technology plans which quantitatively assesses project contribution to overall goals and missions.

Felder (2008) presents an approach to evaluation of energy policy proposals which goes beyond firm-level decision making and places proposals in the context of the world energy system. The focus of this work is not on projects themselves, but on the policies which ultimately effect selection and implementation of energy projects. Energy projects are noted to have several common characteristics, including that they are large-scale efforts which involve assets with long lives and significant sunk costs, with significant uncertainty around future costs and demand, sensitivity to incentives, and produce a product critical to modern society. Felder posits that energy policy proposals should be evaluated in terms of their scope, time required to achieve objectives, feedbacks, impact on available options, costs relative to alternatives, and assumptions for success.
2.3.3 Applications to Technology Transitions

Limited work has also been done applying systems engineering methods and principles directly to the problem of technology transitions and, in some cases, incorporating the ideas of TM.

Wang and Chen (Wang & Chen, 2008) applied a technology transitions approach, utilizing MLP and TM, to propose a framework for achieving a low-carbon economy in China. An analysis of the niche, regime and landscape levels specific to the Chinese economy is offered and the potential role of disruptive innovations is specifically discussed. Similarly, Kivits, Charles and Ryan (2010) utilized the TM framework to analyze possibilities for technological transition within the commercial aviation sector. Their analysis of the aviation system includes assessment of infrastructure, stakeholder networks, and potential strategies and pathways.

Chappin and Dijkema (2008) propose a research agenda for systems design processes to support TM objectives and processes. They recommend that the design process of goal establishment, determination of objectives and constraints, definition of the design space, development and execution of tests, and selection of alternatives can be applied to TM processes. An analysis of this design process relative to technology transitions identifies a research agenda which includes development of performance indicators suitable for assessing system transitions, identification of appropriate design variables, and development of tests (with an emphasis on modeling and simulation tools) to compare different designs’ suitability for effecting system transitions.
The literature discussed in Section 2.3 demonstrates that systems engineering is a suitable approach to the problems of sustainability, portfolio management, and technology transition. However, research within the field of systems engineering has not, so far, provided an integrated approach or methodology which addresses the processes of sustainable technology transition via management of portfolios of projects. Instead, these areas have been addressed individually via portfolio management approaches and identification and application of systems engineering to other specific sustainability problems and processes.

2.4 Architecture Frameworks

Architecting, in the systems engineering sense, refers to the art and science of defining and documenting the structure and interfaces (both internal and external) of a system. Architectures then are the products, or artifacts, that result from the architecting process. Architectures represent the system of interest in terms of structure and interfaces, as well as the purpose, behaviors, and constraints of the system. Architecture frameworks provide guidance and structure (standards) for the process of architecting and the development of architectures. (Maier & Rechtin, 2009)

Common elements of an architecture framework include views and viewpoints. Architecture views provide different perspectives of the same system, such that information is presented in a way that is relevant to different stakeholders. It is important that views within the architecture are integrated such that consistency between views is maintained. (Sage & Lynch, 1998) Viewpoints provide the format, or blueprint, for the creation of views. Many architecture frameworks also provide an overall conceptualization (depiction) of the architecture framework structure. They may also
include a recommended process for implementation of the architecture framework and development of the architecture model.

Historically architecture frameworks emerged to support the development and/or transformation of large information systems. They have also been used extensively for development of large defense systems and other complex government development programs. As the prevalence of architectures has grown, and the utility of architecture frameworks accepted, international standards for the development of architectures have also emerged. Recently literature has also emerged for the use of architecting outside of the traditional bounds of information and defense systems. Architecture frameworks from each of these areas are discussed next.

The following Sections (2.4.1, 2.4.2, 2.4.3, 2.4.4) offer a survey of various architecture frameworks, their design and use, for the reader who is less familiar with architecting and architecture frameworks. These sections also serve to demonstrate the evolution of architecture frameworks into use within more widespread and special-purpose applications. Finally, common elements of the architecture frameworks surveyed were utilized in the development of the architecture framework which is the product of the research undertaken within this dissertation. Those common elements which were incorporated are discussed in Section 2.4.5.

2.4.1 Information System Architecture Frameworks
Zachman initially introduced his information systems architecture (ISA) framework as a descriptive framework to assist in dealing with the size and complexity of modern information systems. The initial framework presented did not include a prescribed process for implementation. Zachman’s initial architecture concept was
modeled after and somewhat analogous to classical architecture, with perspectives defined to represent the interests of planners, owners, designers, and builders. The initial framework also sought to provide a structure for answering the “what, how, and where” of the system. (Zachman, 1987) Zachman continued to extend his ISA framework and in 1992 published an extension which added the “who, when and why” of the system. This extended ISA framework is presented in Figure 6 below. Rules for use of the framework were also added which specified that: there is no priority or order to the columns in the framework; each column has a simple, basic model; the basic models of each column are unique to that column; each row represents a different perspective (owner, designer, builder); each cell in the table is unique; the combination of all cells in a row constitutes a complete model from the perspective of that row; the framework is recursive in that it can be used for multiple applications or for multiple iterations of the same application. (Sowa & Zachman, 1992)
Around the same time, Spewak was adding to Zachman’s ISA framework concept with the introduction of the Enterprise Architecture Planning (EAP) method. The EAP methodology is essentially an implementation process for the development of the Scope and Enterprise Model perspectives (rows) of the Zachman ISA framework. EAP focuses on the business processes and environment in which the information system operates, and analyzes this environment to develop a plan for IS implementation. The EAP method provides a seven-step sequence of implementation activities as follows: Planning Initiation; Business Modeling; Current Systems & Technology; Data Architecture; Applications Architecture; Technology Architecture; Implementation/Migration Plan. Steps 2 and 3 describe the current environment and processes; steps 4-6 are used to
define the to-be system; the final step documents how to get from the current system to the desired future state. (Spewak & Hill, 1993)

Bernard (2005) built on both the ISA framework and EAP to introduce the EA³ Cube Framework for IS planning and documentation. Underlying his EA³ framework is the idea that enterprise architecture involves both a management program and a documentation methodology, which are driven by business strategies and objectives. The management program and documentation methodology together allow for the development of an integrated, consistent and usable model of the enterprise’s strategic objectives, business processes, information flows and resources. The EA³ process includes the creation of both current and future state views of the enterprise architecture. The EA³ Cube documentation framework cube consists of five hierarchical levels or rows (Goals & Initiatives, Products & Services, Data & Information, Systems & Applications, Networks & Infrastructure), vertical lines of business (mission areas), crosscutting business and technology components (shared services such as facilities, email, administrative activities), and planning threads (activities which are common across the framework such as security, relevant standards, and workforce models). For each component of the EA³ cube, specific artifacts are also prescribed. The documentation framework is utilized to develop current and future state models; an EA Management Plan then must be developed to define the process for moving from the current to the future state.

2.4.2 Federal, Defense, and Other Government Architecture Frameworks
The United States federal government has adopted and mandated the use of architectures for development and management of large systems by federal agencies. The
Clinger-Cohen Act ("Clinger-Cohen Act of 1996," 1996) mandates that federal agencies develop and maintain enterprise IT architectures. In response to this, numerous architecture frameworks have been developed and are in use across the US federal government.

The first architecture framework introduced for use by federal agencies was Federal Enterprise Architecture Framework (FEAF), introduced in 1999. FEAF, developed by the Federal CIO Council (1999) focused on information systems. The objective of FEAF is to promote interoperability between agencies, sharing of information and development processes, organize federal information, and assist federal agencies in the development of architectures and IT investments. FEAF utilizes a segmented approach which allows individual architectures to be developed and then integrated into the larger enterprise-level architecture. FEAF adopts and expands upon the five-layer National Institute of Standards and Technology (NIST) (1989) model. The resulting framework consists of eight components: Architecture Drivers; Strategic Direction; Current Architecture; Target Architecture; Transitional Processes; Architectural Segments; Architectural Models; Standards. Four levels of increasing detail for each of the eight components are also prescribed. The Level III view of the eight FEAF components is shown in Figure 7 below. At the lowest level (Level IV) use of both the Zachman Framework and the EAP approach are endorsed.
Subsequently, the Federal Enterprise Architecture (FEA) program was established by the Office of Management and Budget (OMB) to establish a business-driven model for the federal government. The FEA consists of five interrelated reference models: Performance Reference Model (PRM); Business Reference Model (BRM); Service Component Reference Model (SCRM); Data Reference Model (DRM); Technical Reference Model (TRM). Each reference model has a specific framework which defines the purpose and general content of the reference model. The objective of the FEA is to provide federal agencies with a common framework for describing and analyzing IT investments and enhance collaboration within the federal government. The most recent FEA guidance was released in 2007. (OMB, 2007)

While the objective of the FEA program is to establish a comprehensive reference model approach for the entire federal government, specific agencies, in particular the US Department of Defense (DoD), have also developed architecture frameworks tailored for the types of systems used and developed by their agency. The DoD initially conceived
the Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Architecture Framework in 1996 and then released an updated version in 1997. (DoD, 1997) The C4ISR AF delineated three interrelated views – System, Technical, and Operational – with specific products defined to articulate each view. Though focused on C4ISR applications, the approach outlined in the C4ISR AF was also stated to be applicable to other relevant DoD functions.

Ultimately, the C4ISR AF evolved and expanded into the Department of Defense Architecture Framework (DoDAF). The current DoDAF version 2.02 was released in 2010. (DoD, 2010) DoDAF is the prescribed framework for use within DoD. DoDAF includes models which, when populated with data relevant to the system of interest, generate views of the system. DoDAF also allows for “fit-for-purpose” views which can be defined and used as needed in addition to the standard DoDAF views. Programs can decide which DoDAF views are necessary for their system, as well as which toolset to use in the generation of DoDAF architectures. DoDAF 2.0 represents a shift away from the organizing structure of System, Technical and Operational views to a data-centric structure which consists of the viewpoints depicted in Figure 8 below. As in previous versions, each viewpoint has defined specific products which document that view.
International agencies have also adopted the use of architecture frameworks for defense systems. Two examples are the NATO Architecture Framework (NAF) and the United Kingdom’s Ministry of Defence Architecture Framework (MODAF).

The UK’s MODAF is an EA framework developed by the UK Ministry of Defence (MOD) to support planning and management of defense activities. The current MODAF version 1.2.004 was released in May 2010. Initially developed based on DoDAF, the MODAF EA framework has since been significantly evolved and extended. Similar to DoDAF, MODAF defines views which, when completed, provide a model of the system or area of interest. MODAF defines seven types of views: Strategic; Operational; Service-Oriented; Systems; Acquisition; Technical; and All. (MOD, 2010)

The North Atlantic Treaty Organization (NATO) developed the NATO Architecture Framework (NAF), incorporating concepts from DoDAF as well as other international
architecture framework standards including MODAF. The NAF is intended to support the acquisition, deployment and interoperability of international military capabilities. The latest version of NAF, version 3.0 released in 2007, adds new view groups for Capability, Service-Oriented, and Programme in addition to the All, Operational, Systems, and Technical views, as well as an underlying metamodel. (NATO, 2007)

2.4.3 International Standards for Architecture Frameworks

The Reference Model for Open Distributed Processing (RM-ODP) framework was developed by the International Standards Organization for distributed processing software applications. RM-ODP defines five viewpoints for the specification of large-scale IT systems: the enterprise viewpoint which covers the purpose, scope and policies relevant to the system; the information viewpoint which is concerned with the types of information used in the system and any constraints on that information; the computational viewpoint which entails the functional decomposition of the system into objects and interfaces; the engineering viewpoint which captures the required infrastructure; the technology viewpoint which defines the selected technology for the system. The RM-ODP architecture standard also specifies the characteristics required for a distributed processing system to be considered “open.” (ISO/IEC, 2011)

The Open Group Architecture Framework (TOGAF) was originally developed in 1995 and the latest version (9.1) was released in December 2011. TOGAF is focused on enterprise architectures to support enterprise information systems development. TOGAF documentation consists of seven parts which define key concepts, a step-by-step approach, guidelines for use, structured metamodel, building blocks, and common artifacts, taxonomies, reference models, organizational capabilities and resources
required for development of an architecture. A high-level depiction of the TOGAF content framework is given in Figure 9 below. The TOGAF content framework defines the content of a completed architecture, while the Architecture Development Method (ADM) defines the process for creating the architecture. Similar to Bernard’s EA³ cube, the TOGAF ADM defines a process for moving from a current state of the enterprise system to a desired future state. (TOG, 2011)

![Figure 9: TOGAF Content Framework (The Open Group, 2011)](image)

IEEE 1471, which focused on software-intensive systems, was adopted by ANSI and become ANSI/IEEE 1471 in 2001. Through subsequent revisions, ANSI/IEEE 1471 has since been expanded to be applicable to general systems as well as software products and services and is now known as ISO/IEC/IEEE 42010. ISO/IEC/IEEE 42010 provides definitions and requirements for architecture descriptions and architecture frameworks. To comply with the standard, architecture frameworks must specify concerns and the stakeholders associated with those concerns, viewpoints that document those concerns, and correspondence rules that provide for integration of those viewpoints. (ISO/IEC/IEEE, 2011)
2.4.4 Other Applications of Architecture Frameworks

Browning (2009) introduced a Process Architecture Framework (PAF) to provide integrated views of the processes used to plan and manage the development of complex systems. Representations of processes can include (but aren’t limited to) flowcharts, Gantt charts, Design Structure Matrices, schedules, text narratives, IDEF diagrams, value stream maps, and stock-and-flow diagrams. A PAF would provide an organizing structure and repository where all of these models could be kept and updated, views generated to support decision maker’s needs, and changes in project plans could be promulgated to all stakeholders.

Schuck (2010) applied the concepts of extended enterprise architecture to the application of national park protection. Schuck proposes a network-centric approach to protection and monitoring of natural assets, with an architecture that incorporates (among other things) sensor information and control, weather data, ecological data, social practices, species information, and enforcement and regulatory practices. An example is offered where a specific tool, SemPar VIEW is already in use for a network-enabled extended enterprise architecture application for the management of multi-mission US Coast Guard operations.

The COIM (CLIOS-OPM Integrated Method) was recently introduced by Osorio, Dori and Sussman (2011) for understanding the architectures of complex socio-technical systems. Their approach is also targeted to understanding the evolution of such architectures. COIM combines the Object Process Methodology (OPM) with the Complex, Large Interconnected Open Socio-Technical (CLIOS) Process. OPM allows for the decomposition of a system and understanding a system’s underlying processes,
thus capturing the form and function of a system and its associated subsystems. However, OPM does not allow for analysis of social and contextual aspects of systems. Thus the researchers incorporated the CLIOS process, in particular the Representation Stage of the process which provides for representation of institutional aspects and broader context of a socio-technical system. CLIOS does not provide a structure for decomposition or representation of form and function, hence the combination with OPM. COIM provides a process for the examination of a socio-technical system’s setting, its architectural evolution over time, and a detailed representation of the system. COIM acknowledges the significance of technical, social, political and economic factors in driving a system’s design.

Lai, Deng Chin and Peng (2011) took a modified approach to Hall’s (1969) three dimensional approach to develop an architecture for service businesses. Their approach adds a five-step process of Concept Exploration, System Development, Verification and Validation, Disposition and Delivery, and Maintenance and Distribution to Hall’s time dimension.

Cloutier et al (2010) provide an overview of Reference Architectures, including reference architectures which have been developed for Space Data Systems and an information technology security architecture for the State of Arizona. Reference Architectures are then defined as capturing “the essence of existing architectures, and the vision of future needs and evolution to provide guidance to assist in developing new system architectures.” (Cloutier, et al., 2010, p. 17) Here again we see both the spectrum of applications of architectures, as well as recognition of the idea of architectures evolving over time. Their work also recognizes that Reference Architectures should
capture business aspects and customer context in addition to technical aspects of the system.

Even within defense applications, the importance of context is recognized in recent works. Hallberg, Andersson, and Olvander (2010) introduced an agile architecture framework for command and control (C²) systems that documents not only the design of the C² system, but also supports elicitation of requirements and traces to operational activities of human actors.

Each of these recent applications demonstrates an expanded awareness of the broad applicability of the use of architecture frameworks beyond traditional information and defense system applications to problems which incorporate technical as well as social, economic, environmental, and process aspects. The architecture framework developed within this research represents another special-purpose architecture framework which, similar to some of the frameworks discussed in this section, deals with processes, socio-technical elements, and complex system changes over time.

2.4.5 Summary of Architecture Frameworks
Numerous other architecture frameworks, standards and approaches exist and are in use in various industries and applications. The frameworks presented here were intended to provide an overview of common architecture frameworks as well as a broad spectrum sample of architecture frameworks and their applications. A summary of the architecture frameworks discussed above is presented in Table 1 below.
<table>
<thead>
<tr>
<th>Architecture Framework</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zachman’s Framework (1987)</td>
<td>Enterprise information systems</td>
</tr>
<tr>
<td>Spewak’s EA Planning (1992)</td>
<td>Enterprise information systems, associated business processes and functions</td>
</tr>
<tr>
<td>Bernard’s EA³ Cube (2005)</td>
<td>Enterprise information system planning and documentation</td>
</tr>
<tr>
<td>NATO AF (NAF) (2007)</td>
<td>International military capabilities</td>
</tr>
<tr>
<td>TOGAF (2009)</td>
<td>Enterprise information systems</td>
</tr>
<tr>
<td>RM-ODP (2011)</td>
<td>Distributed software processes</td>
</tr>
<tr>
<td>ISO/IEC/IEEE 42010 (2011)</td>
<td>Software-intensive systems, general systems, software products and services</td>
</tr>
<tr>
<td>SemPar View (2010)</td>
<td>National park protection</td>
</tr>
<tr>
<td>COIM (2011)</td>
<td>Complex socio-technical systems and their evolution</td>
</tr>
<tr>
<td>Lai, Deng Chin and Peng (2011) modified Hall’s approach</td>
<td>Small service businesses</td>
</tr>
<tr>
<td>Reference Architectures (Cloutier, 2010)</td>
<td>Numerous applications, incorporating technical and business aspects, customer context</td>
</tr>
</tbody>
</table>

The progression of the use of architecture frameworks from information system-focused applications to a broader focus and applicability was also shown above. Recent
work commonly recognizes the importance of business, social, process and environmental context as well as the evolutionary nature of architectures and systems.

The architecture framework developed in this research is intended for application to portfolios of sustainable technology projects (systems) and incorporates social, economic, environmental, and process elements, as well as the concept of system evolution over time.

Other elements of architecture frameworks reviewed above were also incorporated into the architecture framework developed in this research. Several of the frameworks surveyed include an implementation approach, including EAP, EA³, TOGAF, and COIM. Proposed implementation approaches for the architecture framework developed in this research is presented in Section 5.4. In the survey of architecture frameworks it was also seen that most frameworks have a high-level conceptual structure (such as those shown in Figures 7, 8 and 9) as well as detailed viewpoints – which align to the overall conceptual structure – to guide the development of views within the architecture description products. Lastly, a square or cube structure is commonly used (as in Zachman’s framework, EA³, and the DoDAF depiction of Figure 8) to illustrate the conceptual structure of the architecture framework. Use of a square or cube format is useful for depicting two- and three-dimensional relationships between different elements of the architecture construct. Similarly, Section 5.2 presents the final conceptual structure of the architecture framework developed in this research as a cube.
Chapter 3 – Research Framework

3.1 Research Gap
Several gaps and areas for further research within the field of transitions to sustainable technologies were noted in Section 2.2 above. Some specific areas for further research noted above are particularly relevant for the research undertaken in this dissertation. Specifically, SNM scholars noted struggles around knowledge retention after the completion of experiments, sharing of lessons learned between efforts, and better understanding how to manage portfolios of experiments to facilitate niche development. There is recognition and concern by transitions scholars that knowledge gained during experiments is easily lost or not readily shared between efforts. (Kemp, et al., 1998; Schot & Geels, 2008) In recognition of this need to provide practitioners interested in applying SNM and/or TM with usable tools and skills, some scholars are working to develop a “competence kit” to make the concepts of SNM and TM transferable to practitioners involved in transition experiments. (Raven, Bosch, & Weterings, 2010)

Other scholars identified a need to better emphasize and understand technology-social interactions, and to undertake more systematic case study research. A better understanding of the context of transition efforts, in terms of institutional and implementation challenges, is also needed.

It is the premise of the research described in this dissertation that each of these gaps can start to be addressed by applying a systems engineering approach to the management of transition efforts. The crux of the problem to be addressed by this work was well described by Raven:
“Although transition management is a promising concept, it has proven to be difficult to apply the principles in practice. (Dignum, 2006) An important difficulty identified by practitioners is to link the strategic level of vision making and planning with the operational level of experimenting. Actors at the operational level argued that they were often missing a clear framework for experimentation. And at present no monitoring occurred to feed lessons from experimentation back into the strategic level.” (Raven, 2007, p. 2392)

TM researchers also acknowledge that TM itself is not an instrument to be used in managing efforts, but rather a perspective on transitions. (Kemp & Rotmans, 2004) However, practitioners do require instruments that they can use to guide and facilitate their efforts. The research undertaken in this dissertation provides such an instrument.

There is precedence for the use of systems engineering for problems of sustainability, portfolio management, and technology transitions, as seen in Section 2.3 above. In the field of sustainability, a systems engineering approach has been identified for eco-industrial parks, challenges for systems engineering in addressing sustainability have been identified (need for systematic frameworks, metrics, integrated models, better understanding of system boundaries), and optimization/modeling approaches have been applied to the selection of energy and transport systems. Systems engineering approaches in the area of portfolio management and selection have generally focused on optimization of portfolio selection decisions. Specific to technology transitions, systems engineering approaches have been seen in the use of the TM framework and concepts for the analysis of specific problems and situations, as well as in the development of a research agenda for TM and the engineering design process.
All of this prior work indicates that systems engineering is a suitable approach and toolset for the issues and research gaps identified. In fact, Abbott (2007) and Beckerman (2000) argue for the applicability of systems engineering to address the challenges of complex systems, while Edge (2003) argues for greater collaboration between STS scholars and, among others, engineers to improve the field of STS. However, there has not been a significant amount of work to-date which directly integrates or applies the concepts of systems engineering to the field of transitions to sustainable technologies. In this research, that gap is addressed by starting with the utilization of a common systems engineering approach: systems architecture, specifically the development of a new architecture framework tailored to the management of portfolios of sustainable technology projects, based on theories from the field of transitions to sustainable technologies.

Shown in Section 2.4 above is a discussion of common and emerging applications of architecture frameworks. Architecture frameworks are seen here as suitable to the application of sustainable technology transitions for several reasons. An objective of architecting includes specifying a system, which includes technical as well as human and organizational systems, such that the end result meets user needs, integrates and interfaces appropriately, and is able to evolve over time. Major interfaces of consideration include the technology, human and organization elements of a system. Architectures should guide the development of implementation plans and evolutionary processes for systems. (Sage & Lynch, 1998) Architecting bridges the gap between the current state and a desired future state, and is tailorable to the architecting of socio-
technical systems. (Maier & Rechtin, 2009) All of these aspects of architectural objectives are pertinent to technology transition processes.

While the use of architecture is well-established within the field of systems engineering, its broader use across disciplines is still in the early stages. Browning’s (2009) work further paved the way for the use of architecture frameworks to manage processes, in addition to the traditional use of architecture frameworks for systems (products and enterprises). Technology transitions involve processes, people, and products. Architecture is also recognized as a useful tool for understanding the form, function, and overall behavior and evolution of socio-technical systems. (Osorio, et al., 2011) Osorio, Dori and Sussman’s COIM approach applies architecture frameworks to the analysis of a socio-technical system’s form, function, and associated outside influences. COIM is used to understand the architectural evolution of a socio-technical system in a backward-looking manner, while the approach developed in this research is forward-looking with the objective of enhancing efforts to guide a system’s evolution. The stated benefits of COIM are similar to the objectives of the research undertaken here: understanding the technical, social, political and economic factors which affect system evolution; understanding the effect of these and other factors on system evolution via an architectural approach; enabling decision-making for problem-solving associated with these factors.

Rouse (2007), in the development of a complex systems research agenda, acknowledged the role of architecture in understanding and designing complex systems. Developing approaches to architecting complex systems is described as one of the fundamental areas of research that needs to be addressed. He further discusses
characteristics of complex systems as including (but not limited to) being comprised of numerous elements, having a large number of stakeholders which affect the system, encompassing complex issues such as sustainability, and multiple objectives. Again we see that technology transition projects and processes are a form of complex systems, and Rouse’s work explicitly acknowledges the need for architectural approaches to address the challenges associated with these systems. Similarly, the emerging field of Engineering Systems (ES), which builds upon LTS and STS theories, is meant to explain and offer solutions to problems involving large-scale complex socio-technical systems with environmental, social, functional, technical and process domains. Within the field of ES, a stated area for research is to provide frameworks to conceptualize and model engineering systems in order to provide meaningful and structured information about the systems of interest. (Bartolomei, Hastings, Neufville, & Rhodes, 2012)

3.2 Research Objectives and Questions

The initial research question which drove this research was to understand the potential applicability of systems engineering approaches, including systems architecting, to the management of processes for transitions to sustainable technologies. After an examination of the literature summarized above, and further exploration of the concepts, the research question was refined into more specific objectives and questions. The research objectives and questions are as follows. In each case, the research objective guided the research effort undertaken. Accomplishing the stated research objective(s) allowed the researcher to answer the associated research question(s).

O1: Develop an architecture framework for the management of portfolios of sustainable technology projects which leverage theoretical literature on
transitions to sustainable technologies. The architecture framework is developed utilizing the literature discussed above, and then refined via a case study process. The objective of the architecture framework, based on the literature, is to facilitate learning, monitor ongoing status of projects, identify commonalities and enhance integration between projects, and facilitate project execution. **Q1: What is the architectural structure of portfolios of sustainable technology projects in a technology transitions context?**

**Q2: Demonstrate the use of the architecture framework with real-world case studies of portfolios of sustainable technology projects.** Case studies are identified where organizations are conducting multiple projects to develop and/or implement sustainable energy technologies. Information on these portfolios of projects is systematically collected and implemented within the architecture framework construct, yielding areas for enhancement and refinement of the architecture framework. **Q2: How do the characteristics and dynamics of real-world portfolios of projects relate to the theoretical concepts underlying the architecture framework?**

**Q3: Identify lessons learned from the application of the case studies to the architecture framework construct.** Lessons learned and significant themes and observations are identified and discussed relative to the architecture framework and the literature. These lessons are applied to modify the design of the architecture framework and to better understand its utility and use. **Q3: What lessons learned can be derived from the development of the architecture framework and subsequent case study use and analysis?**
Each of these objectives is intended to address the problems presented in Chapter 1 around the identification and management of portfolios of projects in a manner that leads to long-term sustainability. The need for development of systems engineering tools, which are suited to these types of efforts and consistent with both technology transition theories and proven systems engineering approaches, is also addressed by these objectives.

The methodology for addressing these objectives and findings relative to these objectives and questions are discussed in Chapters 4 and 5.

**Chapter 4 – Research Methodology**

**4.1 Research Methodology Overview**

After establishing research objectives and questions and conducting a literature review, the primary theories on transitions to sustainable technologies (Strategic Niche Management, the Multi-Level Perspective, and Transition Management) were utilized to develop requirements for the purpose and content of the architecture framework developed in this research. The architecture literature further informed the development of the structure of the architecture framework developed in this research. The resulting complete set of requirements is provided in Table 2 below. These requirements were presented and discussed at the 2011 IEEE International Technology Management Conference (Davis, Mazzuchi, & Sarkani, 2011) and suggestions and feedback were incorporated. A primary take-away from the conference presentation was to ensure the scope of the architecture framework did not focus exclusively on Transition Management at the expense of the other significant theories around transitions to sustainable technologies.
Table 2: Requirements for Development of the Architecture Framework

- Capture the current state and potential future states of the niche, regime, and landscape levels
- Capture the dynamics between the niche, regime, and landscape levels
- Document both social and technological aspects
- Document strategic, tactical, and operational aspects of the transition effort
- Support monitoring of niches, regime processes, the transition arena, transition goals, projects, barriers, opportunities, and learning processes.
- Define stakeholder expectations, societal needs, and capabilities/benefits of new technology(s)
- Facilitate learning from and between projects
- Document the full stakeholder network and stakeholder characteristics
- Define potential pathways, or development trajectories, of the technology(s) for transition
- Denote established targets or goals for technology development, maturation, and benefits
- Reflect both short-term and long-term goals, actions, and benefits
- Document visions or scenarios developed by the stakeholder network
- Document potential/actual impacts up and/or down the value chain
- Capture both supply and demand aspects of the projects and technologies
- Provide an assessment of and progress against the 8 barriers to transition identified by Kemp, Schot and Hoogma (1998) and Tsoutsos and Stamboulis (2005): technological factors; government policy and regulation; cultural and psychological factors; demand factors; production factors; infrastructure; undesirable social and environmental effects; economic factors
- Incorporate the seven dimensions of the socio-technical regime: technology; user practices and markets; symbolic meaning of technology; infrastructure; industry structure; policy and regulations; techno-scientific knowledge (Geels, 2002)
- Accommodate multiple experiments, i.e. a portfolio of experiments
- Adhere to best practices for architecture framework design, development and use and accommodate use by practitioners less familiar with architecture frameworks

Once the requirements for the architecture framework were established, architecture framework development began and was conducted in an iterative fashion with the case...
study efforts. Completion of the case studies and development of the final architecture framework allowed for the identification of lessons learned, conclusions relative to the research objectives and questions, and identification of fruitful areas for future research. Chapters 5 and 6 discuss these results and conclusions in further detail.

The overall research approach is shown in Figure 10 below.

A significant portion of the research time and effort was focused on the development of the architecture framework and the collection of case study data to validate and improve the architecture framework. This effort enabled the development of the architecture framework presented in Chapter 5 through both an inductive and deductive process. A deductive approach is one that is “top-down”, starting with theory, developing hypotheses and instruments to test hypotheses. An inductive approach is “bottom-up”, collecting different views and perspectives through open-ended questions and using these to build up to patterns, themes, theories, and generalizations. The work undertaken here
is pragmatic in that it combines inductive and deductive approaches. (Creswell, 2009; Creswell & Plano Clark, 2011)

This two-pronged inductive and deductive process is depicted in Figure 11 below. Deductively, the theories from the literature review provided a list of requirements for the architecture framework. These were used to develop an initial architecture framework, mechanized in the form of an MS Access database.

Inductively, case studies were used to assess and improve the framework by identifying common themes and issues when the case studies were applied to the initial architecture framework. A case study, for this research, consists of a portfolio of sustainable technology projects being conducted by an organization. For each case study (portfolio of projects), a case study owner was identified to provide information about the portfolio and individual projects. Details about specific case study characteristics are provided in Section 4.3.

Based on the same literature review, and the resulting initial architecture framework, a questionnaire (provided in Section 4.2) was developed to collect case study data. Case studies were identified according to criteria (described in Section 4.3) and contact was made with case study owners to confirm participation. Once the case study data was collected, it was used to populate the architecture framework and, through this process, improve the content and structure of the framework both theoretically and in the form of the MS Access database. The specific processes for collecting case study data, identifying case studies, and operationalizing the architecture framework are discussed.
next. The initial and final architecture frameworks are presented and discussed in Chapter 5.

**Figure 11: Architecture Framework Development and Case Study Process**

**4.2 Case Study Data Collection Questionnaire**

Before identifying and contacting potential case study owners, a questionnaire was developed. This questionnaire is presented in Figure 12. The questionnaire reflects the information required in order to address the requirements identified in Table 2 and to populate the architecture framework as it was initially conceptualized. The first page of the questionnaire provides background information on the research being conducted.
This page was included to provide additional information to potential case study owners to allow them to assess their interest in participating and to self-assess their portfolio of projects’ fit with the research objectives.

The remaining pages are questions to be answered by case study owners. The first group of questions (questions 1-3) concerns the case study’s portfolio of projects as a whole. The second group of questions (questions 4-30) is specific to each project and must be answered for each project in the portfolio.

The last group of questions does not concern the projects or the overall portfolio. Instead they are administrative (such as follow-up procedures), collect biographic information on the case study owners (title/role and years of experience), procedural requirements (privacy concerns and reviewing of results) and, lastly, intended to solicit feedback on the utility and efficacy of the questionnaire itself.

<table>
<thead>
<tr>
<th>Introduction and Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>The purpose of this research is to develop an architectural methodology to support the management of a portfolio of projects related to sustainable and/or clean energy technologies and the transition of such technologies into more widespread use. There is a multi-level perspective theory on the transition of technologies which postulates that technology transitions (into widespread use) occur as a result of interactions at three levels – the niche, regime and landscape levels. Building upon this multi-level perspective of technology transitions there is an emerging theory of transition management which presents a means to stimulate and modulate a transition through the identification and management of a portfolio of projects to develop and experiment with new technologies.</td>
</tr>
<tr>
<td>This research develops an architectural methodology to complement the transition management approach. The following questionnaire is intended to collect information</td>
</tr>
</tbody>
</table>
regarding your organization’s portfolio of projects. The responses will enable development of a representative architecture of the portfolio of projects and refinement of the architectural methodology.

For the purposes of this research, a project can involve the research, development, implementation and/or experimentation with a new technology, technological process, or new application of an existing technology. This may include past, ongoing or planned (future) projects. The focus of this research is on projects which involve technologies which utilize or enhance sustainable and/or clean energy use.

The first part of the questionnaire concerns the overall project portfolio and need only be answered once. The remainder of the questionnaire pertains to each project and should be answered for each project in your organization’s portfolio.

If you prefer to provide verbal, rather than written, responses please let me know and I will schedule an interview(s) at a time convenient for your organization. Also, if an existing document contains answers to one or more questions please feel free to reference that document rather than provide a written response within this questionnaire.

Please do not hesitate to contact me if any questions or concerns arise while completing the questionnaire.

Thank you for your time.

Sincerely,

Kim Davis

[Contact info inserted here]

General Questions

1. Please list the projects you are conducting, including the technology(s) being investigated and current application(s). For each project please also identify the project status (i.e. ongoing, planned, complete).

2. Please describe the primary objectives for the overall project portfolio.

3. Please describe any interrelationships between the projects. (i.e. are the projects complementary to each other in any ways?)
## Project-Specific Questions (Please answer for each project)

4. What are the objectives of this project in the short term and long term? (e.g. technical, economic, social, environmental objectives)

5. What are the capabilities and benefits of this technology? What are the current limitations?

6. What are the major lessons learned so far in this project?

7. Where do you anticipate the demand for this technology to come from? Near term? Longer term?

8. Please describe any significant supply issues associated with producing this technology.

9. Please describe the current technology maturity and expected timeline for technology maturation.

10. What are the environmental effects of producing and using this technology?

11. What are the planned next steps for this project and/or technology?

12. Please describe the current application(s) where this technology is being used/investigated.

13. Please describe any other applications for this technology (either current or anticipated).

14. Who are the current users of the technology within this project? Are there any users of the technology outside of this project?

15. How is the project funded? (e.g. internally funded, externally funded, mixed/joint funding)

16. Please describe any complementary technologies which need to be further developed to support the widespread adoption of this technology.

17. What technology currently dominates the market(s) you anticipate this technology to compete in?

18. Please list any policies or regulations (local, state, national, international) in place which support the use of the current dominant technology.

19. Please describe any policy or regulatory changes which would better support use of this project’s technology.
20. What infrastructure is associated with the dominant technology?

21. Is any new infrastructure required to support this project’s technology? (If so, please describe.)

22. What is the basic science behind the dominant technology?

23. What is the basic science behind this project’s technology? Are any breakthroughs in basic science required to significantly enhance this project’s technology?

24. How does use of this project’s technology differ, from an end user perspective, from use of the dominant technology?

25. Are any significant new skill sets required to produce or use this technology relative to the dominant technology?

26. Could this project’s technology be used in conjunction with the dominant technology? If yes, how so?

27. Please describe any other significant barriers to market entry for this project’s technology.

28. Please describe any market or economic shifts which would encourage (or limit) use of this project’s technology.

29. Please describe any cultural, demographic or political shifts which would encourage (or limit) use of this project’s technology.

30. Please list the stakeholders involved in this project, their role in the project as well as their desired outcome for the project. (Examples of stakeholders may include any outside organizations, sponsors, early users, policy makers, manufacturers, suppliers, other research institutions, etc.)

Follow-Up

May I contact you with any follow-up questions? If so, please provide preferred contact information.

Please provide any feedback regarding this questionnaire.

Are there any questions which were not included in this questionnaire which you would consider to be relevant?
Would you be willing to review the project portfolio architecture which results from this questionnaire and provide feedback?

Please describe any specific information privacy/masking concerns or requirements.

Would you like to discuss the results of the research when complete?

What is your current title/role and number of years experience?

Figure 12: Case Study Questionnaire

4.3 Case Study Characteristics

Three case studies were used to test, validate and improve the architecture framework developed in this research. Each case study consists of multiple sustainable technology projects being conducted within an organization. Criteria for identifying and selecting case studies were as follows:

1. Organizations which are conducting projects to evaluate new sustainable technologies;

2. Organizations must be conducting more three or more such projects;

3. Projects must involve technologies, and/or associated technological processes, which are intended to enhance environmental sustainability;

4. Projects may involve research, development, use, or implementation of a new technology or involve new applications of an existing technology.

The initial approach was to work with a single organization (Department of Defense) and collect information on portfolios of projects being conducted by different departments (Services) within that organization. However, access to the appropriate personnel to collect the required case study data became an issue. After this, a search was conducted to identify other organizations conducting portfolios of projects which
could serve as case studies. The search was conducted primarily within industries where
the researchers had access – public sector (primarily Federal Government),
transportation, and/or defense. An internet search was conducted to identify
organizations and portfolios of projects which met the four criteria listed above. Emails
were sent and, where possible, phone calls made, in order to establish initial contact with
potential case study owners and introduce the research objectives. Organizations which
expressed an initial interest and willingness to participate were provided with the case
study questionnaire before committing to scheduling time to collect the case study data.
Because the list of questions is quite extensive, it was important to obtain buy-in and
commitment from case study owners up-front before proceeding with the collection of
data on their portfolio of projects. This also allowed the case study owners to prepare
and to determine which projects were appropriate relative to this research.

Ultimately three organizations committed to participating in the case study data
collection efforts. The first organization was a small entrepreneurial technology
development and manufacturing firm. The projects this organization described focused
on development of new technologies, associated manufacturing processes, and efforts to
enhance marketability of these technologies. Three projects which involved development
of new materials, processes, and technologies for energy generation were selected for
discussion by this organization. The second organization was a large private industry
transportation firm engaged in projects to evaluate new technologies and their potential to
enhance business processes, environmental regulatory compliance, environmental
impacts, and profitability. This organization elected to discuss eight projects, each
involving technologies to reduce energy consumption and/or move to cleaner energy
technologies and improve operational efficiency for both transport systems and operational facilities. The third organization was a large facilities-oriented Government agency conducting projects with some developmental aspects, but primarily focused on evaluating the applicability – both technological and economic – of existing sustainable energy technologies within new applications suited to this organization’s mission. Data on eight projects involving technologies to reduce energy consumption and greenhouse gas emissions associated with large commercial facility operation was collected from the third organization.

Each organization identified a case study owner to respond to the questionnaire and any follow-up efforts. All interviewees (case study owners) were at a Director-level, or equivalent, or higher and were in a position of responsibility and oversight over the portfolio of projects discussed. Each case study owner opted to provide answers to the questionnaire via phone interview. This was easier for the case study owner and also allowed for collection of richer and lengthier responses than a written response would have offered. The phone interviews were recorded and subsequently transcribed. The transcriptions were reviewed and utilized to enter responses into the architecture framework (MS Access database).

4.4 Architecture Framework Operationalization

The conceptual architecture framework was operationalized as a relational database utilizing Microsoft Access (2010). Data collected from the case studies was entered into the database in the appropriate data fields (in MS Access Tables) in order to generate the resulting architectural views (MS Access Reports). A description of the final content and
The correspondence between questionnaire items and architecture framework views is given in Table 3 below. Table 3 identifies the source (questionnaire item number and/or analysis of other views) for the information in each view (MS Access Report).

The specifics of each view within the final architecture framework are discussed further in Chapter 5. The MS Access Reports correspond directly to the names of the architecture framework views (i.e. for each view a corresponding Report was generated in MS Access). The information in the MS Access Reports (views) is drawn from Tables within the database. Tables are related to each other as appropriate (as depicted in Appendix A). For example, Niche, Regime and Landscape tables are related to allow for mapping in a one-to-one or one-to-many fashion depending on the particulars of a given project/portfolio.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Views</th>
<th>Questionnaire Item #(#s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admin</td>
<td>Overview &amp; Background</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td></td>
<td>Acronyms &amp; Definitions</td>
<td>N/A</td>
</tr>
<tr>
<td>Project</td>
<td>Project Overviews</td>
<td>1, 3, 4, 6, 9, 11, 12, 17</td>
</tr>
<tr>
<td>Objectives</td>
<td>Objectives by Time Horizon</td>
<td>2, 4</td>
</tr>
<tr>
<td></td>
<td>Objectives by Stakeholder</td>
<td>2, 4, 30</td>
</tr>
<tr>
<td></td>
<td>Objectives by Project</td>
<td>2, 4</td>
</tr>
<tr>
<td>Stakeholders</td>
<td>Stakeholder Overviews</td>
<td>15, 30</td>
</tr>
<tr>
<td>Aspect</td>
<td>Views</td>
<td>Questionnaire Item #(s)</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------</td>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>Current State</td>
<td>Current Niches</td>
<td>5, 7, 8, 10, 12, 14, 16, 21, 23, 24, 25, 27</td>
</tr>
<tr>
<td></td>
<td>Current Regimes</td>
<td>17, 20, 22, 24, 25</td>
</tr>
<tr>
<td></td>
<td>Current Landscape</td>
<td>18, 27, 28, 29</td>
</tr>
<tr>
<td>Future State</td>
<td>Future State Visions</td>
<td>N/A (Summary of Future State Views)</td>
</tr>
<tr>
<td></td>
<td>Future Niches</td>
<td>5, 7, 8, 9, 11, 13, 14, 16, 21, 23, 25, 26</td>
</tr>
<tr>
<td></td>
<td>Future Regime</td>
<td>20, 21, 22, 23, 24, 25, 26</td>
</tr>
<tr>
<td></td>
<td>Future Landscape</td>
<td>19, 27, 28, 29</td>
</tr>
<tr>
<td>Analysis</td>
<td>Benefits &amp; Limitations</td>
<td>5, 27</td>
</tr>
<tr>
<td></td>
<td>Supply &amp; Demand</td>
<td>7, 8</td>
</tr>
<tr>
<td></td>
<td>Policy &amp; Regulations</td>
<td>18, 19, 29</td>
</tr>
<tr>
<td></td>
<td>Niche-Regime Analysis</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Niche-Landscape Analysis</td>
<td>5, 18, 27, 28, 29 (Requires analysis of Current &amp; Future Niche and Landscape Views)</td>
</tr>
<tr>
<td></td>
<td>Regime-Landscape Analysis</td>
<td>17, 19, 28, 29 (Requires analysis of Current &amp; Future Regime and Landscape Views)</td>
</tr>
</tbody>
</table>

Chapter 5 – Research Findings

5.1 Initial Architecture Framework

Based on the literature review and list of requirements, an initial conceptualization of the architecture framework was developed. This initial framework, as shown in Figure 13, was presented at the International Association for Management of Technology Conference in Miami Beach, FL in April 2011. (Davis, Sarkani, & Mazzuchi, 2011) The initial concept was organized around the projects. Each project was assumed to have its own unique niche, regime, and landscape context. The first layer of the framework was documentation of the current state of each project (and associated niche, regime and landscape), followed by documentation of future state(s). Additional layers within the
framework allowed for documentation of stakeholders, objectives, and cost/benefit attributes. These last three layers can span multiple projects as well as the niche, regime, and landscape levels as appropriate. For example, some objectives may apply at the portfolio level and affect all projects, while some may apply only to an individual project. The same is true for stakeholders and elements of the cost/benefit analysis. The cube structure allows for relating projects (in a one-to-one, one-to-many, or many-to-many fashion, as appropriate) to niche/ regime/landscape elements in both the current and future state, as well as to stakeholders, objectives, cost/benefit characteristics. The “stitches” between the rows and columns depict the potential interrelationships between projects and between conceptual levels.

Figure 13: Initial Architecture Framework Conceptualization
A further iteration of this concept was presented at the 2011 IEEE International Technology Management Conference. In this iteration, the same conceptual cube was presented with an additional layer of implementation discussed. The cube was overlaid with the Transition Management cycle (as shown in Figure 14) and the focus on different layers of the cube at different points during the cycle was discussed. The concept behind Figure 14 was to map an implementation approach to the TM cycle, with different layers of the architecture framework being focused on at different stages within the cycle. During problem structuring and visioning, it was posited that defining and analyzing the future state, stakeholders, and goals and objectives would be the focus of efforts. During development of the transition agenda the focus shifts to the current state and future state, mapping out interim states to achieve the desired final future state. When executing projects, the focus shifts again to management of current state, stakeholders, and monitoring of progress against goals and objectives. Finally, when evaluating and learning, analysis and evaluation (and revision) is conducted against the future state, goals and objectives, and cost/benefit aspects of the portfolio.
As discussed in Chapter 4 above, one of the significant elements of feedback received during this presentation was not to focus too exclusively on Transition Management, leaving out the application of other significant theories. The next iteration of the architecture framework construct and implementation approach then was driven by practical implementation via real world case studies as well as feedback from the conference. When the implementation processes presented later in Section 5.4 were developed the basis was primarily the experience from the case studies vice the theory of TM.

5.2 Final Architecture Framework

Next the collection of case study data began. Once the data was collected, it was loaded into the initial architecture framework structure (database). As this process
progressed, the database was modified to accommodate lessons learned from real-world data and projects. These modifications are detailed in Section 5.3. Along with this, the overall conceptualization of the framework itself changed. The final conceptualization of the architecture framework is shown in Figure 15 below.

The final cube consists of seven aspects: Administrative; Analysis; Projects; Current State; Future State(s); Objectives; Stakeholders. Each aspect consists of one or more views. As discussed in Section 2.4 above, views provide a description of the system of interest with a particular perspective or set of concerns in mind. Viewpoints specify the structure and content for the development of views. (Maier & Rechtin, 2009) Here, we use the term aspect to mean a collection of views which have a similar purpose and content, and use aspects for clarity of discussion and overall representation of the architecture framework structure. The content of each aspect, and its associated views, is
discussed below. Of note, each view consists of a basic textual representation as well as suggested attachments which would constitute additional artifacts within the view. The detailed viewpoints used to generate these views are provided in Appendix B.

**Administrative Aspect.** The Administrative aspect consists of two views: Overview and Background; Acronyms and Definitions. The Overview and Background view has two parts. The first part describes the overall portfolio of projects, the purpose of the projects, how the portfolio relates to the organization’s objectives and mission as well as a discussion of the organization conducting the projects. The second part offers a brief background on the architecture, specifically the theoretical basis for the architecture framework and a description of the purpose and use of the architecture. The Acronyms and Definitions view provides a forum to define any acronyms used in the architecture, as well as define any terms as appropriate. Individual architectures may have unique terms which must be defined. There are also common terms which are recommended for definition in all architectures utilizing the framework, including: niche, regime and landscape; short-term, medium-term and long-term as it relates to objectives; definitions of types of niche-regime relationships (for example, symbiotic, substitutional, complementary).

**Project Aspect.** The Project aspect consists of a single view. This view, Project Overviews, presents information on each project in the portfolio in a consistent and structured manner. Key information about each project, including an overall description of the project and technology, project status, next steps and lessons learned, application, relationship to other projects, associated regime and landscape, are captured in this view.
Typical project description and project management documents are suggested for attachment to this view.

**Objectives Aspect.** The Objectives aspect consists of three views, each presenting the same objectives but organized according to different parameters. The three views organize the objectives by time horizon (short-term, medium-term, long-term), stakeholder (the stakeholder(s) which contribute each objective), and by project.

**Stakeholders Aspect.** The Stakeholders aspect consists of a single view, Stakeholder Overviews. This view describes each stakeholder and their role relative to each project. It is important to note that stakeholder information is also incorporated into Analysis views as appropriate even though there is only one view within this aspect which is specific to discussing the list of stakeholders. Additional stakeholder information, such as biographies and organization charts, can be attached to this view.

**Current State Aspect.** The Current State aspect consists of three views, one each to capture the current state of Niche(s), Regime(s) and Landscape(s) associated with the portfolio of projects. The Current Niches view provides an overview of niche characteristics, including capabilities, benefits, limitations, users and skill sets, supply and demand, complementary technologies, basic science required, current and required infrastructure, environmental effects of production and use. The Current Regimes view provides an overview of characteristics of the dominant technological regime relative to the project technology and application, including a basic description, associated technology, users and skill sets, infrastructure and basic science required. The Current Landscape view describes the landscape underlying the projects’ niche and regime,
including description of current landscape and associated market, cultural, economic, demographic and political conditions and trends. The Current State views are used extensively in performing the analyses required to capture the niche/regime/landscape relationship dynamics in the later views associated with the Analysis aspect.

**Future State Aspect.** The Future State aspect includes four views. Three of the views are structured the same as the three Current State views, capturing the same information about the niche, regime and landscape, only projected into a future state rather than documenting the current state. The fourth view is a summary of the three other Future State views, which allows for a quick look at the future state vision(s) associated with each project.

**Analysis Aspect.** While the Project, Objectives, Stakeholders, and Current State aspects allow for documentation, oversight and management of the portfolio of projects, and the Future State aspect supports visioning, the views within the Analysis aspect are where the information collected in the other views comes together to allow for analysis and discussion of opportunities and barriers to project and technology success. The Analysis aspect consists of six views. Three of the views – Benefits & Limitations, Supply and Demand, and Policy & Regulations – provide analyses of different facets of each project. The other three views – Niche-Regime Analysis, Niche-Landscape Analysis, and Regime-Landscape analysis – document the dynamics (both actual and potential) between the conceptual levels of the niche, regime and landscape as they relate to each project.
For each current and potential future application, the Benefits & Limitations view presents an overview of the actual and potential benefits and limitations allowing for further analysis such as SWOT or ROI analyses. The benefits and limitations described in this view are kept consistent with those documented in the Current and Future Niche views.

The Supply & Demand view discusses both the supply and demand sources (and any challenges or limitations) associated with the current niche application and with potential future niche applications. Kemp, Schot and Hoogma (1998) recognized that both the supply and demand side of the market must evolve in order for a new technology to successfully compete. Again, this view can be used to support further more formal analyses and consistency between the data in this view and the data in the Current and Future Niche views is enforced.

The Policy & Regulations view describes all polices and/or regulations, both existing and potential, which currently affect or have the potential to affect the niche and/or regime, either positively or negatively. This view identifies the policy/regulation, discusses the effect on the niche and/or regime, and identifies any stakeholders with the potential to influence the policy or regulation. In this way, impacts of policy and regulation can be identified and monitored and plans to influence the policy process can be developed as appropriate.

The Niche-Regime Analysis view describes the relationship of the niche and associated project technology with the dominant technological regime. The relationship can take several forms, some examples of which are substitutional (the niche technology
wholly replaces the dominant technology for that application), complementary (the niche technology supplements the dominant technology for that application), and symbiotic (the two technologies can be integrated to work together for that application). Other definitions for technological relationships can be defined by the architect as needed to suit the specific situations of other portfolios.

The Niche-Landscape Analysis documents an assessment of the barriers and/or opportunities for the niche (and associated project technology) based on the economic, market, cultural, political, and demographic elements of the associated landscape. Similarly, the Regime-Landscape Analysis offers an assessment of landscape factors which are either stabilizing or de-stabilizing for the dominant technological regime.

The results of each Analysis view can be used to inform further iterations of the portfolio and architecture. The Benefits & Limitations view may identify niche areas which are more or less appropriate for the project technology. Issues uncovered in the Supply & Demand view may show a systemic need across projects for further investment in expanding supply networks. The Policy & Regulations view may identify a critical gap in the stakeholder network – a key potential regulation with the potential for significant impact which cannot be addressed by any of the existing stakeholders. The Niche-Regime-Landscape Analysis views should highlight future directions which are more or less promising for future projects or expansion of current projects. This feedback can be incorporated into both future state visions and into planning for future execution of the project portfolio. In this way the Analysis views support decision-making within the cyclic processes of Strategic Niche Management and Transition Management.
Table 4 summarizes the content of each aspect and associated views. At a minimum, each view consists of a textual representation of some defined set of characteristics of the portfolio/project. The purpose and content of this textual representation for each view is described in the third column of Table 4; the complete content and layout of the textual representation for each view is given in Appendix B. For some views, additional artifacts, or attachments, are identified which may be beneficial for further depicting those characteristics of the project/portfolio; these suggested attachments are listed in the fourth column of Table 4. Architects utilizing the framework are not limited to these suggested attachments; instead these are intended to provide suggestions for artifacts which are not industry or organization specific as a starting point. Individual organizations or industries may commonly produce other documents or analyses related to or expanding upon the content of the views and such artifacts could also be attached.

**Table 4: Overview of Aspects and Views in Final Architecture Framework**

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Views</th>
<th>Purpose and Content</th>
<th>Suggested Attachments (Artifacts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admin</td>
<td>Overview &amp; Background</td>
<td>Provide an overview of the organization and portfolio.</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>Acronyms &amp; Definitions</td>
<td>Provide list of acronyms and definitions.</td>
<td>None.</td>
</tr>
<tr>
<td>Project</td>
<td>Project Overviews</td>
<td>Provide an overview of projects in the portfolio. Includes description of project, technology, current status, relationships to other projects, lessons learned, next steps, objectives, application (niche), dominant regime, current landscape.</td>
<td>Project overviews, charters, plans, schedules, reports. Technology description (technical) documents. Lessons learned documents.</td>
</tr>
<tr>
<td>Aspect</td>
<td>Views</td>
<td>Purpose and Content</td>
<td>Suggested Attachments (Artifacts)</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Objectives</td>
<td>Objectives by Time Horizon</td>
<td>Identify objectives organized by time horizon. Includes objective description and associated project(s).</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>Objectives by Stakeholder</td>
<td>Identify each stakeholder’s objectives. Includes objective description, time horizon, and associated project(s).</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>Objectives by Project</td>
<td>Identify the objectives for each project, and associated objective description and time horizon.</td>
<td>None.</td>
</tr>
<tr>
<td>Stakeholders</td>
<td>Stakeholder Overviews</td>
<td>Provide an overview of all stakeholders and their roles relative to the projects/portfolio. Includes stakeholder name, description, associated projects, and description of stakeholder role(s).</td>
<td>Organization charts. Biographies. Company or agency overviews, histories, mission and vision statements.</td>
</tr>
<tr>
<td>Current State</td>
<td>Current Niches</td>
<td>Provide an overview of the current niche for each project. Facilitate analysis of niche/landscape and niche/regime fit. Includes description of current capabilities, benefits, limitations, users and skill sets, supply and demand, complementary technologies, basic science required, current and required infrastructure, environmental effects of production and use.</td>
<td>Technical descriptions of project, complementary technologies. Environmental analyses (expected and realized). Infrastructure descriptions and analyses. User profiles.</td>
</tr>
<tr>
<td>Aspect</td>
<td>Views</td>
<td>Purpose and Content</td>
<td>Suggested Attachments (Artifacts)</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Current State</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Regimes</td>
<td>Provide an overview of current regime for each project. Facilitate analysis of niche/regime and regime/landscape fit. Includes description of current dominant technological regime and associated technology, users and skill sets, infrastructure and basic science required.</td>
<td>Technical descriptions of technologies. Infrastructure descriptions and analyses. User profiles.</td>
<td></td>
</tr>
<tr>
<td>Current Landscape</td>
<td>Provide an overview of current landscape for each project. Facilitate analysis of niche/landscape and regime/landscape fit. Includes description of current landscape and associated market, cultural, economic, demographic and political conditions.</td>
<td>Economic trend charts. Market analyses (graphs). Demographic trend charts and analyses.</td>
<td></td>
</tr>
<tr>
<td><strong>Future State</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Future State Visions</td>
<td>Provide an overview of potential future states for each project. Includes an overview of current and potential future niches, regimes, and landscapes.</td>
<td>None.</td>
<td></td>
</tr>
<tr>
<td>Aspect</td>
<td>Views</td>
<td>Purpose and Content</td>
<td>Suggested Attachments (Artifacts)</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>-------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Future State</td>
<td>Future Regime</td>
<td>Provide an overview of potential future regimes for each project. Facilitate analysis of niche/ regime and regime/landscape fit. Includes a description of future regimes, associated technology, users and skill sets, infrastructure and basic science required.</td>
<td>Technical descriptions of technologies. Infrastructure descriptions and analyses. User profiles.</td>
</tr>
<tr>
<td></td>
<td>Future Landscape</td>
<td>Provide an overview of potential future landscapes for each project. Facilitate analysis of niche/landscape and regime/landscape fit. Includes a description of potential future landscapes and associated market, cultural, economic, demographic and political conditions.</td>
<td>Economic trend charts and predictions. Market analyses and predictions. Demographic trend charts, analyses and predictions.</td>
</tr>
<tr>
<td>Analysis</td>
<td>Benefits &amp; Limitations</td>
<td>Provide an overview and analysis of the benefits, limitations, and challenges for each project. Includes a description of current and future applications, description of current and potential future benefits and limitations for each project.</td>
<td>Cost/benefit analysis, SWOT analysis, ROI analysis, user feedback.</td>
</tr>
<tr>
<td></td>
<td>Supply &amp; Demand</td>
<td>Provide an overview of current and potential future supply and demand for each project to allow identification of current or potential issues.</td>
<td>Value chain analysis.</td>
</tr>
<tr>
<td>Aspect</td>
<td>Views</td>
<td>Purpose and Content</td>
<td>Suggested Attachments (Artifacts)</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Policy &amp; Regulations</td>
<td>Identify policies / regulations which currently or may impact projects and any stakeholder influence. Includes a description of the policy, affected niche and/or regime and nature of effect, identifies stakeholders with potential to influence policy / regulation and nature of that influence.</td>
<td>Expanded policy / regulation descriptions and analysis. Historical or planned efforts to influence policy / regulations.</td>
</tr>
<tr>
<td></td>
<td>Niche-Regime Analysis</td>
<td>Identify the project technology’s relationship to the current dominant technology and allow analysis of opportunities to integrate with or replace the current technology. Includes an overview of the niche and regime and description of the niche-regime relationship.</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>Niche-Landscape Analysis</td>
<td>Provide an analysis of niche fit with current landscape across market, cultural, economic, demographic and political dimensions. Allows identification of opportunities, challenges and barriers.</td>
<td>None.</td>
</tr>
<tr>
<td></td>
<td>Regime-Landscape Analysis</td>
<td>Provide an analysis of current technological regime fit with the current landscape across market, cultural, economic, demographic and political dimensions. Allows identification of opportunities to change the regime as well as barriers supporting regime stability.</td>
<td>None.</td>
</tr>
</tbody>
</table>
Templates for each view are provided in Appendix B. While each of the above views were developed using actual project information from each case study, the case study owners placed privacy requirements on the use of their project information. Because of these privacy requirements, actual case study data is not presented within this document. However, the templates in Appendix B reflect the lessons learned and structure utilized to capture the case study architecture descriptions.

Each view has a consistent format. At the top of the view is the title of the view, followed by a description of the purpose of the view. The body of the view contains the textual information required for each view. At the bottom of the view, suggested attachments (additional artifacts) are listed. If these files were attached within the MS Access database, the content of the files themselves could be shown after the text portion of the view. While the templates show a single page, many of the views would have multiple pages. Many of the views are organized by project such as, for example, the Benefits and Limitations view. In such cases, the template shows the output expected for a single project; this output would then be iterated for each project in the portfolio.

Returning to the initial list of requirements for development of the architecture framework, we see that this conceptualization, and its implementation in the MS Access format, meets the prescribed requirements. A discussion of how each requirement is met is offered in Table 5 below.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Final Architecture Framework Feature(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture the current state and potential future states of the niche, regime, and landscape levels</td>
<td>Captured within the views of the Current State and Future State aspects.</td>
</tr>
<tr>
<td>Capture the dynamics between the niche, regime, and landscape levels</td>
<td>This requirement is accomplished through analysis of Current and Future State Views. The resulting dynamics are documented in the Niche-Regime Analysis, Niche-Landscape Analysis, and Regime-Landscape Analysis views.</td>
</tr>
<tr>
<td>Document both social and technological aspects</td>
<td>Social aspects of niche and regime includes users and skill sets; landscape includes cultural, demographic and political conditions. Technological aspects of niche include capabilities, benefits, limitations, complementary technologies and basic science; regime includes technology and basic science; project includes technology maturity and applications. These are captured in the Stakeholder, Policy &amp; Regulations, Project, Current State and Future State views.</td>
</tr>
<tr>
<td>Document strategic, tactical, and operational aspects of the transition effort</td>
<td>The strategic level of visioning is captured in the Future State views. The tactical level of building agendas and networks is captured in the Project, Niche, Objective, and Stakeholder views. The operational level of implementation and experimentation is captured in the Project view.</td>
</tr>
<tr>
<td>Support monitoring of niches, regime processes, the transition arena, transition goals, projects, barriers, opportunities, and learning processes.</td>
<td>Monitoring of the Current State, Project, Stakeholder, Objective, and Analysis views collectively achieves this requirement.</td>
</tr>
<tr>
<td>Define stakeholder expectations, societal needs, and capabilities/benefits of new technology(s)</td>
<td>Stakeholder expectations, including societal expectations/needs, are captured in the Objectives. Capabilities and benefits are captured in the Niche views.</td>
</tr>
<tr>
<td>Requirement</td>
<td>Final Architecture Framework Feature(s)</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Facilitate learning from and between projects</td>
<td>Lessons learned are documented in Project Overviews. Relational database design allows for multiple projects and mapping to same or different niches, regimes, landscapes, stakeholders, objectives, etc.</td>
</tr>
<tr>
<td>Document the full stakeholder network and stakeholder characteristics</td>
<td>Stakeholders are documented in the Stakeholder Overview. Stakeholder alignment to objectives is documented in the Objectives by Stakeholder view. Stakeholder influence on policy and regulation is documented in the Policy &amp; Regulations view.</td>
</tr>
<tr>
<td>Define potential pathways, or development trajectories, of the technology(s) for transition</td>
<td>Relational database design allows for multiple Future State views to be captured for each project. These multiple views can align to multiple potential pathways and/or interim steps along a transition pathway.</td>
</tr>
<tr>
<td>Denote established targets or goals for technology development, maturation, and benefits</td>
<td>The architecture captures Objectives, as well as technology maturation plans and next steps in the Project view.</td>
</tr>
<tr>
<td>Reflect both short-term and long-term goals, actions, and benefits</td>
<td>Objectives are captured along with the time horizon in the Objectives by Time Horizon view. Next steps are captured in the Project view. Benefits are captured in the Niche views.</td>
</tr>
<tr>
<td>Document visions or scenarios developed by the stakeholder network</td>
<td>Future State views are used to capture visions/scenarios.</td>
</tr>
<tr>
<td>Document potential/actual impacts up and/or down the value chain</td>
<td>Supply and Demand analysis view documents current and potential future supply and demand sources and issues. Current and Future Niche views also capture supply and demand characteristics, as well as other relevant infrastructure characteristics.</td>
</tr>
<tr>
<td>Capture both supply and demand aspects of the projects and technologies</td>
<td>Supply and demand characteristics are captured in the Current Niche and Future Niche views, as well as the Supply and Demand view.</td>
</tr>
</tbody>
</table>
5.3 Lessons Learned from Case Studies

There are several significant differences between the final cube – which was enhanced through the case study process – and the initial cube which was developed in response to the theoretical underpinnings alone. First, an Administrative aspect was added. In working with the case study data it became apparent that it was necessary to provide context and references for the overall architecture. The Administrative aspect
provides a place and structure to introduce the purpose of the architecture, the overall portfolio of projects, and define terms and acronyms for consistent use throughout the architecture. The definition of terms such as “short-term” and “long-term” is likely to be different across organizations and even within organizations where a broad network of stakeholders are involved. Providing a forum for formally documenting definitions allows for all users of the architecture to have a baseline understanding of the taxonomy used.

Second, the Niche, Regime, and Landscape are no longer defined as aspects (or layers) of their own; instead they are elements of current and future state descriptions. Further, the new structure allows for multiple projects to be tied to the same niche, regime and/or landscape if appropriate. In the Future State, projects can be tied to more than one niche, regime, and/or landscape if appropriate (i.e. if multiple development trajectories are under consideration).

Objectives and Stakeholders are maintained as distinct aspects in this conceptualization, but are modified to span not just multiple projects but also both current and future state scenarios. The Objectives aspect was also expanded to encompass more than one view. After collecting the case study data it became apparent that different organizations may have different approaches to defining and viewing objectives. One of the case study organizations had very distinct objectives for each project with minimal commonality across projects, making the projects themselves the primary characteristic for organizing objectives. Another case study organization placed higher emphasis on time horizon of objectives, primarily to accommodate justifications for project funding. The third case study organization had several consistent objectives across projects (as
well as some project-unique objectives), but noticeably objectives originated from numerous distinct stakeholders each with different interests in the project outcomes.

Finally, in reviewing the case study data it became apparent that the crux of the framework’s utility is in its ability to provide a forum for conducting various types of analyses. For this reason, an Analysis aspect was added which consists of more analysis views than simple cost/benefit. After collecting the case study data, it was clear that while the other aspects are very useful for organizing vast amounts of information about a portfolio of projects, the rigor of the Analysis views is what enables the critical thinking to support future planning and decision-making. In order to allow for this rigor, multiple views were necessary to capture different facets of the dynamics of large-scale portfolios of projects.

One challenge was identified which could not be formally addressed within the architecture framework structure. For each project, different conceptual levels of analysis for the regime and landscape could be identified. Some case study organizations went immediately to the national industry level when discussing the dominant regime while others described the broader global industry. For example, when looking at a new technology to replace diesel engines, one could consider the dominant technological regime to be the diesel engine as used within a particular industry. Or if the technology involves alternative fuels, one could assess the regime as the dominant competitor within the alternative fuels market. The regime of interest could also be the broader transportation system within which the diesel engine is a component. The choice of how to conceptualize the regime cannot be enforced within the architecture framework structure. However, in evaluating the case studies it seems appropriate to advise the
architect to choose a regime conceptualization which is consistent with the goals of the project(s) and portfolio. If a solution for a particular industry is the ultimate goal, then the regime level of analysis should focus on the industry characteristics and dynamics. Likewise, if the objective is to compete within the existing alternative fuels marketspace then the regime level of analysis should focus on that space. This challenge of identifying the appropriate level of analysis is not unexpected due to the complex systems nature (Beckerman, 2000) of the architectures developed.

With regard to the case study questionnaire itself, the most common feedback was that the project seemed interesting and the questions generated thought. One area for improvement in the questionnaire was noted by one of the interviewees who recommended that timeframe be more explicitly incorporated into the questions. For example, the answers to some of the questions would have been significantly different if asked a few years in the past so capturing the time elements, and changes over time, would be important to understanding the project dynamics. This lack of longitudinal study and data is addressed as a limitation later in Chapter 6.

5.4 Architecture Framework Implementation

The architecture framework described here could be used by any organization which meets the four criteria presented earlier: conducting projects to evaluate new sustainable technologies; conducting three or more such projects; interested in technologies, and/or associated technological processes, which are intended to enhance environmental sustainability; involved in research, development, use, or implementation of a new technology or new applications of an existing technology. Organizations can be
corporations, Government entities, or non-Governmental organizations who are interested in developing and increasing the application of sustainable technologies.

For the purposes of this research, the architecture descriptions were developed based on answers to a questionnaire. However, if an organization were to develop an architecture description using the framework presented above, a more robust process for development and implementation would likely be both required and useful. Many architecture frameworks have an associated recommended implementation process, such as Spewak’s EAP method, Bernard’s EA³, and TOGAF, as described in Section 2.4 above.

While the case study efforts undertaken here did not directly evaluate potential implementation approaches, it was observed that organizations are at different levels of maturity and execution of their portfolios of projects. Based on the maturity of an organization’s portfolio and status of project execution, different implementation approaches may be necessary. For organizations with an existing, mature portfolio of ongoing projects, a bottom-up approach may be most appropriate. However, for organizations just beginning to plan and execute projects, a top-down approach may be appropriate. Potential bottom-up and top-down implementation approaches are discussed next.

In a bottom-up approach (depicted in Figure 16), the first step an organization would take would be to document the existing projects within the architecture framework construct. This would include documenting the known objectives and stakeholders for the projects. From here, the organization would focus on identifying and documenting
the current state of the niche, regime, and landscape features. As discussed above, this would include identifying the appropriate conceptual level of analysis based on the overall portfolio objectives. Once the current state was documented, the next step is to complete visioning so that potential future states can be captured within the architecture and tied to the existing projects. With the baseline data now captured within the architecture, the organization can now turn to conducting analyses and documenting these within the Analysis views. This final step should lead to insights not previously realized and influence further iterations of the portfolio architecture. Iterations could include revising or expanding potential future states, adding stakeholders to the network, updating or expanding project objectives, or modifying and even adding projects to the portfolio.

Figure 16: Conceptual Bottom-Up Approach for Documenting Existing Portfolios of Projects
In a top-down approach (depicted in Figure 17), ongoing projects do not already exist. In this situation, organizations initially utilize the architecture framework to build and evaluate a portfolio of potential projects before moving into project execution and monitoring utilizing the framework. The first step in this approach is to identify and document the organization’s objectives for the potential portfolio of projects. Based on these objectives, potential future states are documented. These future states should be documented at a level of analysis appropriate to the objectives previously identified. Potential projects are then identified and documented based on the objectives and desired end-state(s). Along with each project, stakeholders must be identified. The current state of the niche, regime and landscape features associated with potential projects is then assessed and documented. Finally, the Analysis views are used to evaluate the potential portfolio of projects. This process again can iterate until the portfolio of projects is solidified, and continue to iterate as project execution progresses. As in the top-down approach, iterations could include revisions or expansions of potential future states, stakeholders, objectives, or even projects.
5.5 Conclusions to Research Objectives and Questions

This section returns to the research objectives and questions presented in Section 3.2 and offers a discussion of how the work undertaken and described in this dissertation addresses the research objectives and answers the associated research questions.

**O1: Develop an architecture framework for the management of portfolios of sustainable technology projects leverage theoretical literature on transitions to sustainable technologies. Q1: What is the architectural structure of portfolios of sustainable technology projects in a technology transitions context?**

Sections 5.1 and 5.2 describe the architecture framework developed during the course of this research. The architecture framework development methodology was elaborated in Chapter 4, which described the foundation of the architecture framework development process as the theoretical literature on transitions to sustainable technologies (SNM, MLP, TM). Using this literature as the theoretical basis, the framework was initially
constructed, and later refined through a case study process. In this way, leverage of the literature on transitions to sustainable technologies was built into the architecture framework, and later confirmed in Table 5 through an assessment of the framework’s performance relative to the requirements derived from the literature. Through the case study process, the ability of the architecture framework to document portfolios of sustainable technology projects was demonstrated.

The architectural structure of portfolios of sustainable technology projects in a technology transitions context is seen in the final architecture framework construct presented in Figure 15. This structure includes the following seven aspects: Administrative; Analysis; Projects; Current State; Future State; Objectives; Stakeholders. The Objectives and Stakeholders aspects span projects as well as the current and future state of the portfolio. The Analysis aspect encompasses all aspects of the portfolio. Niche, regime, and landscape characteristics are captured across projects, and in terms of both current and future state characteristics. The Administrative aspect provides a foundation for entry into the architecture and for understanding the portfolio of projects and associated architectural descriptions. Further details of the final architectural structure were provided in Section 5.2.

**Q2: Demonstrate the use of the architecture framework with real-world case studies of portfolios of sustainable technology projects.**  
**Q2: How do the characteristics and dynamics of real-world portfolios of projects relate to the theoretical concepts underlying the architecture framework?**
Architecture descriptions of three real-world case studies of portfolios of sustainable technology projects were documented using the architecture framework developed in this research, thus demonstrating its practical use. Section 4.3 provides the details of the case studies, while Section 4.4 discusses how the framework was operationalized to generate real-world architecture descriptions representing the case study portfolios.

Several lessons were learned regarding the characteristics and dynamics of real-world portfolios of projects relative to the theoretical concepts which produced the initial architecture framework conceptualization. These lessons learned are detailed in Section 5.3. Ultimately, the characteristics and dynamics of real-world portfolios were similar enough to the theoretical concepts such that the final architecture framework, after incorporation of lessons learned from the case studies, met all of the requirements established from a review of the theoretical literature (see Table 5 for details). However, there were modifications to the framework based on case study lessons learned. For example, the reality of the necessity of an Administrative aspect to define and standardize terms and provide pertinent background information was apparent when conducting the case studies. The analysis of the portfolio was not as readily emergent from the architectural structure as initially thought, so additional Analysis views (supply/demand, policy and regulations, inter-level analyses of the niche, regime and landscape levels) beyond cost/benefit considerations were developed to provide the necessary level of structure and rigor to enable these analyses. Finally, consistent with the literature, the appropriate conceptual levels were not readily obvious when documenting the case study portfolios. This was expected based upon review of the literature, and was not
structurally addressed in the framework. Instead, guidance to the architect was offered to tailor the conceptual level of analysis around the objectives of the portfolio.

*O3: Identify lessons learned from the application of the case studies to the architecture framework construct. Q3: What lessons learned can be derived from the development of the architecture framework and subsequent case study use and analysis?*

Following the case study process outlined in Chapter 4, numerous lessons learned were captured from the case study efforts and elaborated upon in detail in Section 5.3. One major lesson learned included the need to move from a project-focused structure to a more portfolio-level structure, with project details still captured and readily accessible. In the final architecture framework, the current and future states are conceptually built around the niche, regime, and landscape levels, and linked to projects as appropriate. This also allows for projects to be associated with one or more niches, regimes and/or landscapes within the current and/or future state, which was found to be a more accurate representation of the reality of the projects within a common portfolio. It was also noted that each portfolio of projects was unique, with emphasis in different areas within the architectural structure. The structure developed requires that all pertinent information be captured, but also allows the architect to focus time and detail, through greater description or additional artifacts, where most appropriate to the portfolio of interest. Other lessons learned which impacted the architecture framework structure were the need for an Administrative aspect and the need to offer different ways of viewing the Objectives associated with the portfolio.
Chapter 6 – Conclusions

In this research, an architectural methodology and framework was developed for planning and managing portfolios of projects as part of the process of transitioning to sustainable technologies. This research explored the applicability of architectures, a systems engineering approach, to processes of transition to sustainable technologies.

6.1 Overview of Research, Results and Benefits

Through this work, several significant research objectives and questions were addressed, and lessons learned were documented. An architectural structure for portfolios of sustainable technology projects in a technology transitions context was developed and analyzed, building on theories of technology transition as well as fundamental architectural approaches. This architectural structure was evaluated and refined using real-world case studies, which yielded improvements in the structure as well as lessons learned around the characteristics of real-world efforts relative to the theoretical concepts underlying the architecture framework. Key lessons learned included maintaining a portfolio-level structure with project details still captured and linked appropriately, establishing greater structure for performing analysis of the portfolio of projects, the addition of an administrative aspect to the architecture, and allowing for flexibility in use of the architecture based on the areas of emphasis emergent in different organizations’ architectures. All of the research objectives laid out at the beginning of this research were met, and all of the research questions were answered.

Refinements were made to the approach during the conduct of the research. For example, out of practicality and access issues, the sources of case studies was modified from collecting multiple case studies out of a single, large organization to collecting case
studies from dispersed, unrelated organizations. Ultimately the case study approach undertaken offered a better cross-section of organizations and most likely yielded more insightful results by engaging organizations with different missions and scope. Peer feedback from conferences was also used to re-focus efforts, for example moving back to a more general focus on theories of transitions to sustainable technologies vice focusing more heavily on the Transition Management implementation process, and placing significant emphasis on implications and lessons learned from the case study process.

The architectural framework and approach developed was found to be useful in illuminating themes within the different case study architectures. For example, it was noted that policy and regulations played a more significant role in some portfolios than others, while costs and market competitiveness or technology maturity were more heavily emphasized in others. Having an integrated architecture, which documented all of the projects within the portfolio versus having separate architectures for each project, allows the architect to capitalize on commonalities and lessons learned across the projects. For example, projects which are linked to the same dominant regime may be able to learn from each other about different challenges and opportunities associated with the regime.

In general, the research being undertaken was well-received by the case study participants and there was an acknowledgement that such a tool for documenting and guiding their efforts did not currently exist. The project management tools currently used for managing the portfolios of projects within the case studies were primarily around cost and schedule tracking and reporting, any mandatory reporting due to grant requirements, and ad-hoc reviews of the overall R&D portfolio. No integrated tools or approaches for documenting and analyzing information about the portfolio of projects that enabled
looking forward and collectively planning for the projects were identified, thus confirming the gap in practice and the need for an integrated architecture framework approach. Case study owners also generally stated that the questions in the questionnaire were good and thought-provoking. Likewise, the research proposals and initial concepts were well received at two conferences, with attendees consistently expressing interest in the work to be undertaken.

Overall, the research objectives to develop an architecture framework consistent with theories of transitions to sustainable technologies, demonstrate the architecture framework’s use with real-world case studies, and identify lessons learned from the case studies were all achieved by this research and discussed throughout this dissertation.

6.2 Limitations
There were some limitations to the research undertaken here. One limitation is that the case studies were conducted at a point in time and, due to access and time constraints, a longitudinal study of the portfolios was not undertaken. Having the ability to observe the portfolios and their evolution over time would likely have yielded additional insights and contributed to further development of the architecture framework.

Similarly, the implementation processes proposed in Section 5.4 were not evaluated via the case study process. The case studies, by necessity of time, all represented ongoing portfolios of projects. Although some included projects still in the planning stages, none of the organizations were still in the very earliest stages of establishing the entire portfolio of projects from scratch.
Lastly, again due to access and time constraints, responses to the questionnaire were obtained from a limited number of individuals (two or less) from each organization. Ideally, when developing the architecture for a portfolio of projects, the inputs and perspectives of multiple stakeholders would be solicited and incorporated.

6.3 Future Research

Significant areas for future research remain. Future research could include expanding this study to address the limitations identified, for example conducting a longitudinal study of a portfolio of projects and methodically evaluating implementation approaches. The undertaking of additional case studies in general would also likely yield additional insights and enhancements to the architecture framework. An evaluation of the utility of the architecture framework and approach developed here, as compared to other architectural and portfolio management approaches, could also be undertaken.

Other future research areas could include expansion of the theoretical considerations to include consideration of the traditional R&D portfolio management process. The R&D portfolio management process followed by most advanced organizations includes three steps: resource allocation; evaluation of new and ongoing R&D activities; final selection of a portfolio of R&D activities. (Pereira & Veloso, 2009) An extension of the research completed in this dissertation could be to evaluate the applicability and appropriateness of the architecture framework developed here to this general three-step R&D portfolio management process. For example, consideration of resources required is not explicitly included in the architecture framework developed in this research. Complementing the current architecture framework approach with a design structure matrix-based approach, similar to Suh, et al. (Suh, Furst, Mihalyov, & Weck, 2010), may also allow for further
analysis of disruptiveness and effort required to integrate a new technology. Also, evaluation of existing and potential new views to support formal evaluation and selection activities could be undertaken.

Another possible future area for research would be to study and incorporate the idea of architecting for resilience in systems. Rouse posed the question of “how can architectures enable resilient, adaptive, agile and evolvable systems” (Rouse, 2007, p. 268) as one of the fundamental research questions within the complex systems research agenda. With resilience seen as a system property which can contribute to sustainability (Fiksel, 2003), the idea of incorporating architecting for resilience into the architecture framework developed here, or other suitable architecture frameworks, would contribute to the research field of architecting for sustainability. Additional system features to be architected and analyzed could be explored in terms of contribution to overall system resilience.

Lastly, identification and exploration of additional systems engineering approaches and methodologies to supplement and/or integrate with technology transition efforts and approaches could be undertaken as future areas for research. Examples could include use of formal risk management techniques as part of the SNM or TM process, alignment of SNM or TM processes with systems engineering lifecycle models, or formal knowledge management approaches tailored to technology transition programs.

Achieving sustainability is a significant challenge and one that requires extensive further research. Transitioning to more sustainable technologies, often regarded as a
significant component of the solution set for achieving sustainability, remains a complex, complicated, and unpredictable process. The research undertaken within this dissertation yielded a tool – an architecture framework – for practitioners undertaking projects aimed at transition to sustainable technologies. This architecture framework provides a mechanism for enhanced communication, analysis, and decision-making, potentially leading ultimately to better results when identifying, developing and transitioning technologies for improved sustainability.
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Appendix A: MS Access Database Table Structure
Appendix B: Templates for Final Architecture Framework Views

Overview and Background

**Title of Overall Portfolio/Program**
Provide a high-level introduction to the overarching portfolio/program and a discussion of the purpose, background, and objectives for the portfolio of projects.

**Architecture Background and Purpose**
One theory of technology transitions is that large-scale shifts to new technologies occur as a result of dynamics within and interactions between three levels: niche; regime; and landscape. Niches are protected spaces - specific applications - where technologies can be developed, tested, and improved. Projects are conducted within niches. The regime level is the dominant technological regime for an aggregate of applications. The dominant technological regime consists of the technology itself and associated user practices, skill sets, engineering practices, institutions, and infrastructure. The landscape is the overall context in which niches and regimes exist and includes slow-changing factors such as market, economic, cultural, political and demographic conditions. Over time, changes in landscape conditions can place pressure on the dominant technological regime. At the same time, technologies maturing in niches may aggregate and/or breakthrough and replace or modify the dominant technological regime.

Architectures are a means of documenting the structure and attributes of a system in a structured and organized manner. Architectures can represent the system in a textual form, graphical form, or both. Architecture frameworks provide the structure and organization to guide the development of architectures. In this case, the system is a set of sustainable technology development and/or implementation projects within a common portfolio.

The purpose of this architecture framework is to allow for planning, documentation, and analysis of portfolios of projects intended to develop and deploy new sustainable technologies. This architectural approach allows for analysis of the portfolio and projects with regard to niche, regime and landscape factors to identify challenges, opportunities, and potential paths forward.
Acronyms and Definitions

Acronyms
List of acronyms used throughout the architecture and their definitions.

Definitions
List of terms and their definitions which are key to understanding the architecture and to maintaining consistency of terms throughout the architecture. Examples of terms recommended to be defined for all architectures are provided below. These definitions can be tailored as appropriate.

Complementary One technology can be used to supplement the other, though the technologies themselves are not integrated.
Landscape Overall context in which niches and regimes exist. Includes slow-changing factors such as market, economic, cultural, political and demographic conditions.
Long-term Greater than 10 year time horizon.
Medium-term 5-10 year time horizon.
Niche Protected spaces in which projects are conducted where technologies can be developed, tested, and improved.
Regime Dominant technological regime for an aggregate of applications consisting of the technology and associated user practices, skill sets, engineering practices, institutions, and infrastructure.
Short-term Less than 5 year time horizon.
Substitutional One technology wholly replaces the other.
Symbiotic Old and new technologies can be integrated with each other within the same system.
## Project Overviews

The purpose of this view is to provide a basic overview of the projects in the portfolio.

**[Short Descriptive Project Title]**

[Description of the current niche associated with one or more projects. Identifies technology(s)]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Project Status</th>
<th>Relationship to Other Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of key technology being developed/used/evaluated as part of this project]</td>
<td>[Project Status - Planned, Started, Ongoing, etc.]</td>
<td>[Description of relationships between this project and any other projects within the portfolio]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Application</th>
<th>Lessons Learned</th>
<th>Dominant Technological Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of the application for the technology as part of this project]</td>
<td>[Describe any lessons learned so far from the project]</td>
<td>[Overview of current dominant technological regime associated with one or more projects/niches.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology Maturity</th>
<th>Next Steps</th>
<th>Current Landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of technology maturity - can be based on an established scale or just a qualitative description]</td>
<td>[Planned next steps for this project]</td>
<td>[Overview of current landscape associated with one or more projects/niches/.regimes.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Describe an objective for the specific project or overall portfolio. Objectives can be tied to more than one project.]</td>
</tr>
</tbody>
</table>

*Suggested attachments to this view include project overviews, charters, plans, schedules, reports and technology description documents. Additional details around lessons learned (sourcing and procurement, installation, operations, maintenance).*
### Objectives by Time Horizon

*The purpose of this view is to identify objectives organized by time horizon and which project(s) the objective applies to.*

**[Short, Medium, or Long Term, as defined in the Acronyms and Definitions View]**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Portfolio or Project Level Objective</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Describe an objective for the specific project or overall portfolio. Objectives can be tied to more than one project.]</td>
<td>[Project or Portfolio]</td>
<td>[Short Descriptive Project Title]</td>
</tr>
</tbody>
</table>

### Objectives by Stakeholder

*The purpose of this view is to identify each stakeholders' objectives, which project(s) the objective applies to, and the time horizon for each objective.*

**[Title of Stakeholder Organization]**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Objective Horizon</th>
<th>Portfolio or Project Level Objective</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Describe an objective for the specific project or overall portfolio. Objectives can be tied to more than one project.]</td>
<td>[Short, Medium, or Long Term, as defined in the Acronyms and Definitions View]</td>
<td>[Project or Portfolio]</td>
<td>[Short Descriptive Project Title]</td>
</tr>
</tbody>
</table>
## Objectives by Project

The purpose of this view is to identify the objectives for each project, whether the objective is unique to the project or a portfolio-level objective, and the time horizon for each objective.

<table>
<thead>
<tr>
<th>Short Descriptive Project Title</th>
<th>Project or Portfolio Level Objective</th>
<th>Objective Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Describe an objective for the specific project or overall portfolio. Objectives can be tied to more than one project.]</td>
<td>[Project or Portfolio]</td>
<td>[Short, Medium, or Long Term, as defined in the Acronyms and Definitions View]</td>
</tr>
</tbody>
</table>
## Stakeholders

The purpose of this view is to provide an overview of all of the stakeholders in the portfolio of projects, and their role relative to individual projects.

<table>
<thead>
<tr>
<th>Title of Stakeholder Organization</th>
<th>Brief description of Stakeholder Organization - type of organization, mission, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Role</td>
</tr>
<tr>
<td>[Short Descriptive Project Title]</td>
<td>[Short, descriptive role title. Examples include Sponsor, User, Funding Source, Advocate, etc.]</td>
</tr>
<tr>
<td>Role Description</td>
<td>[Description of Stakeholder’s role relative to a project.]</td>
</tr>
</tbody>
</table>

Suggested attachments to this view include: organization charts; individual biographies; company or agency overviews, history, mission/vision statements.
Current Niches

The purpose of this view is to provide an overview of the current niche for each project, and to facilitate performing the analysis of niche/landscape and niche/regime fit that is documented in other views.

[Short Descriptive Project Title]
[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]

<table>
<thead>
<tr>
<th>Capabilities</th>
<th>Users</th>
<th>Demand</th>
<th>Environmental Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of the capabilities of the project technology within this niche.</td>
<td>List of users of the technology. Can be end users, customers, operators, maintenance/servicing personnel, etc.</td>
<td>Description of current sources of demand for the project technology.</td>
<td>Description of environmental effects, both positive and negative, of utilizing the project technology within this niche. Consider upstream and downstream effects as well.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Skill Sets</th>
<th>Supply</th>
<th>Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of benefits of the project technology, as compared to incumbent technology(s), within this niche.</td>
<td>Description of any new or significantly different skill sets required in order to use the technology within this niche.</td>
<td>Description of current sources of supply for the project technology, and any advantages or limitations associated with the supply system.</td>
<td>Description of infrastructure required to support the project technology. Can be industrial, logistical, workforce, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitations</th>
<th>Complementary Technologies</th>
<th>Basic Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of limitations of the project technology, as compared to incumbent technology(s), within this niche.</td>
<td>Description of any complementary technologies which have been, are being, or need to be developed to work with the project technology.</td>
<td>Description of any advances in basic science which have occurred or could occur to further enhance the project technology.</td>
</tr>
</tbody>
</table>

Suggested attachments to this view include: technical specifications for the primary and complementary technologies; environmental analyses (expected and realized benefits); infrastructure overviews, analyses; user profiles.
# Current Regimes

The purpose of this view is to provide an overview of the current dominant technological regime for each project, and to facilitate performing the analysis of niche/regime and regime/landscape fit that is documented in other views.

**[Short Descriptive Project Title]**

[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]

<table>
<thead>
<tr>
<th>Regime Description</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview of current dominant technological regime associated with one or more projects/niches.</td>
<td>Description of primary technology(s) within current dominant technological regime.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Users</th>
<th>Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of users of the current dominant technology. Can be end users, customers, operators, maintenance/servicing personnel, etc.</td>
<td>Description of existing infrastructure associated with current dominant technological regime. Can be industrial, logistical, workforce, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Skill Sets</th>
<th>Basic Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of skill sets required in order to use the current dominant technology.</td>
<td>Brief description of basic science associated with the current dominant technological regime.</td>
</tr>
</tbody>
</table>

*Suggested attachments to this view include: technical specifications for technologies; infrastructure overviews, analyses; user profiles.*
Current Landscape

The purpose of this view is to provide an overview of the current landscape for each project, and to facilitate performing the analysis of niche/landscape and regime/landscape fit that is documented in other views.

[Short Descriptive Project Title]

Current Landscape

[Overview of current landscape associated with one or more projects/niches/ regimes.]

Market Conditions

[Description of current market conditions - market size, dominant players, key market pressures and strategies, etc.]

Cultural Conditions

[Description of current cultural conditions - relevant cultural trends, user preferences, high-level technology and skill preferences, etc.]

Market Shifts

[Discuss any ongoing or high potential to occur) shifts in the market which could affect the niche and/or regime. For example, significant change in price of a key raw material.]

Demographics

[Description of current demographic conditions - geographic population centers, age and gender distributions, skill levels, etc.]

Economic Conditions

[Description of current economic conditions - relevant macroeconomic conditions/forces, areas of significant investment.]

Political Conditions

[Description of current political environment - political focus areas and pressures.]

Suggested attachments to this view include: economic trend charts; market analysis graphs; demographic trend charts and analysis.
Future State Visions

The purpose of this view is to provide an overview of the potential future states identified for each project to support establishing and analyzing potential visions of the future. More details on the potential future niches, regimes and landscapes is found in other views.

<table>
<thead>
<tr>
<th>Short Descriptive Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Landscape</td>
</tr>
<tr>
<td>Overview of current landscape associated with one or more projects/niches/destinations.</td>
</tr>
<tr>
<td>Dominant Regime</td>
</tr>
<tr>
<td>Overview of current dominant technological regime associated with one or more projects/niches.</td>
</tr>
<tr>
<td>Current Niche</td>
</tr>
<tr>
<td>Description of the current niche associated with one or more projects. Identifies technology(s) used and application.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Future Landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview of potential future landscape associated with one or more projects/niches/destinations.</td>
</tr>
<tr>
<td>Future Regime</td>
</tr>
<tr>
<td>Overview of potential dominant technological regime associated with one or more projects/niches. Note: current projects/niches can be associated with more than one potential future regime.</td>
</tr>
<tr>
<td>Future Niche</td>
</tr>
<tr>
<td>Description of a potential future niche associated with one or more projects. Identifies technology(s) used and application. Note: current projects and niches can be associated with more than one potential future niche.</td>
</tr>
</tbody>
</table>

Suggested attachments to this view include the results of any visioning or brainstorming exercises.
## Future Niches

The purpose of this view is to provide an overview of the potential future niches for each project, and to facilitate performing the analysis of niche/landscape and niche/regime fit that is documented in other views.

**Short Descriptive Project Title**

[Description of a potential future niche associated with one or more projects. Identifies technology(s) used and application. Note: current projects and niches can be associated with more than one potential future niche.]

<table>
<thead>
<tr>
<th>Capabilities</th>
<th>Users</th>
<th>Demand</th>
<th>Environmental Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of the capabilities of the project technology within this potential future niche.]</td>
<td>[List of potential future users of the technology within the niche. Can be end users, customers, operators, maintenance/servicing personnel, etc.]</td>
<td>[Description of potential future sources of demand for the project technology.]</td>
<td>[Description of environmental effects, both positive and negative, of utilizing the project technology within this potential future niche. Consider upstream and downstream effects as well.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Skill Sets</th>
<th>Supply</th>
<th>Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of benefits of the project technology, as compared to incumbent technology(s), within this potential future niche.]</td>
<td>[Description of any new or significantly different skill sets required in order to use the technology within this potential future niche.]</td>
<td>[Description of potential future sources of supply for the project technology, and any advantages or limitations associated with the supply system.]</td>
<td>[Description of infrastructure required to support the project technology. Can be industrial, logistical, workforce, etc.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitations</th>
<th>Complementary Technologies</th>
<th>Basic Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of limitations of the project technology, as compared to incumbent technology(s), within this potential future niche.]</td>
<td>[Description of any complementary technologies which have been, are being, or need to be developed to work with the project technology.]</td>
<td>[Description of any advances in basic science which have occurred to further enhance the project technology.]</td>
</tr>
</tbody>
</table>

*Suggested attachments to this view include: technical specifications for the primary and complementary technologies; environmental analyses; infrastructure overviews, analyses; user profiles.*
Future Regime

The purpose of this view is to provide an overview of the potential future dominant technological regime for each project, and to facilitate performing the analysis of niche/regime and regime/landscape fit that is documented in other views.

<table>
<thead>
<tr>
<th>Short Descriptive Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regime Description</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Overview of potential future dominant technological regime associated with one or more projects/niches. Note: current projects/niches/ regimes can be associated with more than one potential future regime.]</td>
<td>[Description of primary technology(s) within the potential future dominant technological regime.]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Users</th>
<th>Infrastructure</th>
<th>Basic Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>[List of users of the potential future dominant technology. Can be end users, customers, operators, maintenance/servicing personnel, etc.]</td>
<td>[Description of infrastructure associated with the potential future dominant technological regime. Can be industrial, logistical, workforce, etc.]</td>
<td>[Brief description of basic science associated with the potential future dominant technological regime.]</td>
</tr>
</tbody>
</table>

Suggested attachments to this view include: technical specifications for technologies; infrastructure overviews, analyses; user profiles.
Future Landscape

The purpose of this view is to provide an overview of the potential future landscape for each project, and to facilitate performing the analysis of niche/landscape and regime/landscape fit that is documented in other views.

[Short Descriptive Project Title]

Future Landscape

[Overview of potential future landscape associated with one or more projects/niches/technologies/technologies.]

Market Conditions

[Description of potential future market conditions - market size, dominant players, key market pressures and strategies, etc.]

Cultural Conditions

[Description of potential future cultural conditions - relevant cultural trends, user preferences, high-level technology and skill preferences, etc.]

Market Shifts

[Discuss any shifts in the market which have affected / are affecting / could affect the niche and/or regime. For example, significant change in price of a key raw material.]

Demographics

[Description of potential future demographic conditions - geographic population centers, age and gender distributions, skill levels, etc.]

Economic Conditions

[Description of potential future economic conditions - relevant macroeconomic conditions/forces, areas of significant investment.]

Political Conditions

[Description of potential future political environment - political focus areas and pressures.]

Suggested attachments to this view include: economic trend charts and predictions; market analysis graphs and predictions; demographic trend charts, analysis and predictions.
Benefits and Limitations

The purpose of this view is to provide an overview of the benefits and limitations/challenges associated with each project technology and to allow for analysis of relative benefits vs. limitations.

[Short Descriptive Project Title]

Current Application
[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]

Benefits
[Description of benefits of the project technology, as compared to incumbent technology(s), within this niche.]

Limitations
[Description of limitations of the project technology, as compared to incumbent technology(s), within this niche.]

Future Applications
[Description of a potential future niche associated with one or more projects. Identifies technology(s) used and application. Note: current projects and niches can be associated with more than one potential future niche.]

Benefits
[Description of benefits of the project technology, as compared to incumbent technology(s), within this potential future niche.]

Limitations
[Description of limitations of the project technology, as compared to incumbent technology(s), within this potential future niche.]

Suggested attachments to this view include cost/benefit analysis, SWOT analysis, ROI analysis, user feedback.
Policy and Regulations

The purpose of this view is to identify policies and/or regulations which currently impact or have the potential to impact the niche or regime, define the nature of the affect on the niche/regime, and identify any portfolio stakeholders which may have the ability to influence the policy/regulation. The objective is to identify opportunities to positively influence policy/regulations for the benefit of the projects. (For example, ideally policies beneficial to the niche will have project stakeholders who are in a position to advocate for those policies.)

Policy Description:  [Title and description of policy or regulation (current or potential) which affects or could affect one or more projects and/or regimes]

Potential Stakeholder Influence

[Title of Stakeholder Organization]

[Description of Stakeholder’s role in (currently or potentially) influencing the policy or regulation.]

Affected Niche

[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]

Affected Regime

[Overview of current dominant technological regime associated with one or more projects/niches.]

Affect on Niche and/or Regime

[Description of (current or potential) effect of the regulation/policy on the niche and/or regime.]

Suggested attachments to this view include expanded policy/regulation descriptions, policy/regulation analysis, stakeholder history relative to the identified policy/regulation, and any planned efforts to influence policy/regulation decision-making.
## Supply and Demand

The purpose of this view is provide, by project and technology, an overview of the current supply/demand and allow for identification and analysis of any existing or potential issues.

<table>
<thead>
<tr>
<th>Short Descriptive Project Title</th>
<th>Description of key technology being developed/used/evaluated as part of this project</th>
</tr>
</thead>
</table>

### Current Niche

[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]

### Future Niche

[Description of a potential future niche associated with one or more projects. Identifies technology(s) used and application. Note: current projects and niches can be associated with more than one potential future niche.]

### Current Demand Source

[Description of current sources of demand for the project technology.]

### Current Supply Situation

[Description of current sources of supply for the project technology, and any advantages or limitations associated with the supply system.]

### Future Demand Source

[Description of potential future sources of demand for the project technology.]

### Future Supply Situation

[Description of potential future sources of supply for the project technology, and any advantages or limitations associated with the supply system.]

Suggested attachments to this view are a value chain analysis.
# Niche-Regime Analysis

The purpose of this view is to identify the project technology's relationship to the current technological regime and allow for analysis of opportunities to integrate with, or replace, the current technological regime.

<table>
<thead>
<tr>
<th>Niche</th>
<th>Dominant Regime</th>
<th>Niche/Regime Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Description of the current niche associated with one or more projects. Identifies technology(s) used and application.]</td>
<td>[Overview of current dominant technological regime associated with one or more projects/niches.]</td>
<td>[Brief description of the nature of the niche/ regime relationship. Examples: Substitutional, Complementary, Symbiotic]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Discussion of the relationship between the niche and regime. Can the project/niche technology be added to the existing regime in some way or does it replace it?]</td>
</tr>
</tbody>
</table>
# Niche-Landscape Analysis

The purpose of this view is to provide an analysis of niche fit with the current landscape to support identification of opportunities for greater adoption of project technologies as well as challenges or barriers.

## Short Descriptive Project Title

<table>
<thead>
<tr>
<th>Niche</th>
<th>Landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of the current niche associated with one or more projects. Identifies technology(s) used and application.</td>
<td>Overview of current landscape associated with one or more projects/niches/regimes.</td>
</tr>
</tbody>
</table>

## Market Conditions Analysis

<table>
<thead>
<tr>
<th>Market Shifts Analysis</th>
<th>Cultural Conditions Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discussion/analysis of barriers and/or opportunities for the niche based on current market conditions.</td>
<td>Discussion/analysis of barriers and/or opportunities for the niche based on current cultural conditions.</td>
</tr>
</tbody>
</table>

## Economic Conditions Analysis

<table>
<thead>
<tr>
<th>Demographic Analysis</th>
<th>Political Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discussion/analysis of barriers and/or opportunities for the niche based on current economic conditions.</td>
<td>Discussion/analysis of barriers and/or opportunities for the niche based on current political conditions.</td>
</tr>
</tbody>
</table>
Regime-Landscape Analysis

The purpose of this view is to provide an analysis of current technological regime fit with the current landscape to support identification of potential pressures on the regime as well as landscape characteristics supporting regime stability.

**Dominant Technological Regime**
[Overview of current dominant technological regime associated with one or more projects/niches.]

**Current Landscape**
[Overview of current landscape associated with one or more projects/niches/ regimes.]

**Market Conditions Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on current market conditions.]

**Cultural Conditions Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on current cultural conditions.]

**Market Shifts Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on market shifts.]

**Demographics Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on current demographic conditions.]

**Economic Conditions Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on current economic conditions.]

**Political Analysis**
[Discussion/analysis of challenges and/or reinforcing conditions for the current regime based on current political conditions.]