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# Timing Is Everything: Quantifying Regulatory and Market Readiness Levels for Technology Transition Policy Analysis

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**HIGHLIGHTS**

Technology Adoption, Technological Progress, Regulatory Feedback, Market Adoption, Innovation Theory

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**Abstract**

People save for retirement throughout their career because it is virtually impossible to save all you'll need in retirement the year before you retire. Similarly, without installing incremental amounts of clean fossil, renewable or transformative energy technologies throughout the coming decades, a radical and immediate change will be near impossible the year before a policy goal is set to be in place. This notion of steady installation growth over acute installations of technology to meet policy goals is the core topic of discussion for this research. This research operationalizes this notion by developing the theoretical underpinnings of regulatory and market acceptance delays by building upon the common Technology Readiness Level (TRL) framework and offers two new additions to the research community. The new and novel Regulatory Readiness Level (RRL) and Market Readiness Level (MRL) frameworks were developed. These components, collectively called the Technology, Regulatory and Market (TRM) readiness level framework allow one to build new constraints into existing Integrated Assessment Models (IAMs) to address research questions such as, 'To meet our desired technical and policy goals, what are the factors that affect the rate we must install technology to achieve these goals in the coming decades?'

**Keywords**

Technology, Technological Progress, Regulatory Feedback, Market Adoption, Innovation Theory

**Abbreviations**

| | |
|---|---|
| CAFE | Corporate Average Fuel Economy |
| CCS | $CO_2$ Capture and Storage |
| $CO_2$ | Carbon Dioxide |
| DoD | Department of Defense |
| EPRI | Electric Power Research Institute |
| MERGE | Model for Evaluating the Regional and Global Effects of GHG Reduction Policies |
| MINICAM | Mini-Climate Assessment Model |
| MRL | Market Readiness Level |
| NASA | National Aeronautics and Space Administration |
| TRL | Technology Readiness Level |
| TRM | Technology, Regulatory and Market readiness level framework |
| IAM | Integrated Assessment Model |
| IGSM | Integrated Global System Model |
| MIT | Massachusetts Institute of Technology |
| NIMBY | Not in my backyard |
| $NO_x$ | Nitrous Oxides |
| PNNL | Pacific Northwest National Laboratory |
| RD&D | Research, Development and Demonstration |
| R&D | Research and Development |
| RL | Readiness Level |
| RRL | Regulatory Readiness Level |
| $SO_x$ | Sulfur Oxides |
| U.S. | United States |

## 1. Introduction

Modeling the market penetration of energy technologies often give a generalized assessment to the substantial time delays that regulatory and market acceptance barriers can present. Including regulatory barriers in an energy-economic-engineering framework is not difficult mathematically, yet finding the appropriate variables for any given technology can prove challenging. Without the proper market or regulatory signals, the time required for a new energy technology to reach the market and make an impact can extend far beyond what initial estimates may be. Where this becomes a challenge is how to address these time delays for energy technology market penetration scenarios in the decades to come.

In recent years, much has been written on the topics of lowering the $CO_2$ profile for global energy supplies. Increasing the share of natural gas fuels, installing $CO_2$ capture and storage (CCS) technologies on coal-fired power plants, and increasing the share of nuclear and biofuel-based power have all been suggested as potential methods to reduce $CO_2$ emissions (USCCSP, 2007). Coal-based fuels represent the majority share of $CO_2$ emissions from the electricity sectors at both the global level (72%) and in the United States (79%) (IEA, 2012). This represents a large opportunity to decrease $CO_2$ emissions through fuel switching combined with CCS. The challenge with these types of forecasting scenarios lies in the rate of capital turnover, stage of the technology's development level (TRL), the regulatory support and willingness of the market to accept these technologies. Herzog (2010, p. 7) describes the large scale adoption challenge for CCS technologies as, "It is not yet proven that enough storage capacity exists to support CCS [$CO_2$ Capture and Storage] at the gigaton scale and the costs of CCS mitigation may be more than is politically acceptable for the next couple of decades." Similarly, much of the literature indicates a wide range of costs for coal and natural gas-based electricity systems with CCS. This further complicates forecasting a technology's transitions based on electricity price or similar metrics alone given this is somewhat of an evolving criterion to use as a basis (Rubin, 2012; Rubin et al., 2007, 2012).

The drivers of innovation may include several 'technology-push' and 'demand-pull' instruments including R&D investments and meeting regulatory obligations, respectively (Taylor et al., 2005; Kobos et al., 2006; Cheah and Heywood, 2011). Taylor et al. (2005), for example, found that in the U.S., demand-pull instruments such as the threat of coming legislation were more effective in controlling $SO_2$ emissions from power plants than were technology-push mechanisms such as an increase in research, development and demonstration (RD&D) funding. Similarly, recent increases in the Corporate Average Fuel Economy (CAFÉ) vehicle fuel standard in the United States is another good example of the regulatory framework helping technology meet policy (fuel economy) goals. The technology, engineering and timing strategies, arguably, were ready or just about ready to deploy across the vehicle fleet (Cheah and Heywood, 2011). The CAFÉ standards set the 'regulatory rules of the game' to support the technology's adoption (e.g., an incentive structure on the vehicle manufacturers) and the marketplace was ready to adopt the new technologies due to the ease of integration within the existing system (e.g., higher-mileage vehicles, for the most part, continued to use conventional fuels and thereby existing fueling infrastructure – reducing this barrier to entry for widespread market adoption). Similar supply chain management-based approaches have been discussed for the biomass to energy conversion technologies developing throughout the world as well (Mafakheri and Nasiri, 2014).

The same argument to set the 'rules of the game' applies to U.S. electricity sector technologies about the timing and importance of addressing regulatory and market barriers. This challenge spans beyond any one governmental, academic, industry or national laboratory's domain (i.e., multidisciplinary). Without favorable regulatory integration factors, new stationary energy technologies such as enhanced installations of coal-fired power plants with $CO_2$ management or other environmentally-focused technologies may never reach their full market potential due to recent large-scale, low cost domestic supplies of natural gas. Even without these factors in place in the face of other drivers (such as reduced mercury emissions criteria for coal-fired power plants, limited licensing for new nuclear power plants in the face of increasing retirements, and potential $CO_2$ management goals), technologies may take years or decades to reach the installations necessary to meet policy goals. The sooner they are being installed, the sooner these installation goals can be met. Therefore, the timing is everything for technology transitions in the marketplace.

To adequately quantify and develop a method to incorporate time delays due the integration of technology development, regulatory barriers and market adoption, the Technology, Regulatory and Market readiness level framework (TRM) describes the technology, regulatory and market factors required to reach a meaningful market penetration level. With this level, the technology's attributes, such as lower $CO_2$ emissions can then be applied to energy security and $CO_2$ management goals in the coming years.

*1.1 Modeling Technology Transitions*

The TRM framework brings a new capability to Integrated Assessment Models (IAMs) because it explicitly includes both regulatory and market constraints when assessing technology development and rate of market application. Unlike previous techniques that use an ‘S-shaped’ curve (Figure 1) to represent technology transitions and market adoption over time to account for time delays and factors that enhance or inhibit market adoption, this technique explicitly models the factors required before technologies may enter the market as well as those during the early stages of market adoption (Kobos et al., 2003; 2013).[1] The technical approach will develop in three distinct stages by addressing technological, regulatory and market factors built upon the research progress framework of the Technology Readiness Level (TRL) method.

[Figure 1]

This ‘S-shaped’ curve develops such that at the early stages of a technology’s introduction to a new market, the percentage of adoption remains low for a period of time in the ‘acceleration’ phase (Sood et al., 2012). This is often referred to the ‘valley of death’ where a technology will either become more widespread, or simply be eliminated from the market due to a wide variety of factors including competing technologies that provide similar services (e.g., electricity production), regulatory factors, or the lack of forces that promote the technology any further (Weyant, 2011). Next is the ‘take-off’ or inflection stage where given favorable market conditions, the technology adoption percentage increases dramatically (Sood et al., 2012; Frankl, 2012).

To go beyond the classic ‘S-shaped’ curve analysis that aggregates all factors governing the rate of market penetration illustrated in Figure 1, this analysis develops three core modeling modules to add further details to many of these governing factors.

First, the background of modeling technological adoption will be discussed briefly along with the origins of Technology Readiness Levels (TRLs). This will help lay the theoretical and practical aspects of forecasting technological readiness to deploy in the field.

Second, building from this information will help identify the Regulatory Readiness Level (RRL) and Market Readiness Level (MRL) for existing and new electricity technologies. Are $CO_2$ capture and storage (CCS) technologies technically mature enough to deploy to the field? This is a TRL question. The RRL will address questions such as; Do the current electricity markets provide a favorable environment to adopt new technologies on existing plants such as CCS on fossil fuel plants, or develop new ones (e.g., install large numbers of natural gas-fired turbines)? If not, where on the RRL spectrum is the set of regulations, and how long might it take to change the regulations to allow the market to adopt new electricity technologies? A MRL will be developed to ask and address questions such as; Does the manufacturing base for power plant

[1] Interested readers may find mathematical formulations for these ‘S-shaped’ curves as shown in Figure 1 including the common logistic curve, the Gompertz curve and the Bass model to name a few (Kobos et al., 2003; Maier, 1998; Sood et al., 2012).

technologies exist to support several orders of magnitude of growth over the next couple of decades? If not, this will limit the technology's adoption in the marketplace?

Finally, synthesizing all of these efforts within the system dynamics framework allows the analysis to illustrate the TRM framework. The integration of time delays, TRLs and systems insight modeling provides a unique platform unexplored in the current research community. It is believed to be unexplored because (1) classic optimization or general equilibrium models are often not flexible enough to integrate TRLs and (2) adopting TRLs for technology is not new, but utilizing the TRM framework to explore regulatory and manufacturing constraints is a completely new concept. This concept will identify the *value* of timeliness and interconnectedness when modeling them in an IAM in the face of upcoming technical and policy goals (Joffe-Walt, 2008; Joskow, 2010; USCCSP, 2007; Stern, 2007; Wicke et al., 2009).

### *1.2 Applying Technology Transition Methods in Energy Systems Analysis*

In many cases, private industries, academia and many other institutions often do not have the collective incentive or integrated expertise to help guide electricity sector technology installations over the next several decades. Lack of medium-term profit, potential future return (through securing new funds) or the simple inexperience of other research institutions in developing economic and technology adoption forecasts provides those institutions with a multidisciplinary approach a unique opportunity.

To provide additional context, dozens of energy supply and demand forecasting models exist today, yet virtually none of them incorporate the limitations that time delays and Technology Readiness Levels (TRLs) for *regulatory* and *market* forces present when modeling technology manufacturing and adoption (Brown and Chandler, 2008; EMF, 2011). Incorporating the feedbacks seen in supply chain-oriented models in IAMs can be difficult due to their deterministic software architecture, and ignoring historically relevant constraints (scientific, regulatory or financial) can have profound effects on the results. An attempt to understand the social, psychological, technical, and financial factors of research and development using the system dynamics methodology was performed by Roberts (1964). This was, of course, prior to the TRL approach applied to research and development (R&D) progress in the 1980s (Colladay, 1987).

A recent example of select energy supply and demand modeling efforts that could benefit from these types of feedbacks was developed by the U.S. Climate Change Science Program. In that great work that added substantially to the model comparison literature, researchers developed a portfolio of model runs from the IGSM (MIT), MERGE (EPRI/Stanford), and MINICAM (PNNL) models. They offered many future energy technology build up scenarios from 2000 to 2100, but assumed some aggressive levels of installing CCS technologies from virtually none on coal plants in 2020 to roughly 70% of them within a few decades. Studies like this may assume impressive technology build up and deployment rates to meet specific technology portfolio and policy forecast goals (e.g., to meet $CO_2$ emissions goals) yet don't include how a technology's location within the technology's readiness level(s), regulatory support or market condition (supply of the technologies and demand for it) or how this affects the energy portfolio's ability to manage $CO_2$ (McJeon et al., 2011).

Constraints beyond costs and basic engineering are absent in the larger literature because 'expert judgment' or static assumptions represent a basket of regulatory and engineering constraints. Additionally, moving a technology from one TRL level to the next traditionally lack the granularity and technology-specific detail required (e.g., electricity generation and infrastructure technologies may take from several years (natural gas) to several decades (nuclear) to build enough installations to meet their installed GWh or reduced $CO_2$ emissions goals). For example, Freeman and Bhown (2011) determined most post-combustion $CO_2$ technologies (on coal plants) were in the TRL spectrum of 1 – 7 so they are not ready for full system operations and/or ready for commercial application at large magnitudes. Additionally, uncertainty within the climate policy legislation and the potential for regulation is driving great uncertainty as to which fossil fuel-based technology may develop the fastest (e.g., lower initial cost vs. increased efficiency).

The Electric Power Research Institute (EPRI, 2011) estimates it takes four years to construct a new coal-based power plant, one to three years for renewables, seven years for a new nuclear power plant, and up to three years for natural gas power plants. The USCCSP report (2007) forecasts nuclear power to expand in the U.S. around the year 2050. However, it is unclear if there is any domestic or international industry able to increase their manufacturing capability of new power generating stations within these timeframes. Changes in 'opening day' for a new facility or delays throughout the manufacturing or regulatory process can severely hamper a technology's ability to enter or maintain market share via 'lock in' to the status quo due to the perceived unreliability (or inability) of technologies to compete on their own. Additionally, forecasting the cost for the 'first of a kind' new technology or that same technology several decades into the future (the 'Nth of a kind') can prove to be challenging (Herzog, 2010).

*1.3 Replacement and Turnover Time*

Technology transitions take time; up to 50+ years for a full replacement of an energy technology when transitioning from, for example, wood to coal, from coal to petroleum, from petroleum to natural gas and nuclear, from natural gas to large-scale renewables (Nakicenovic, 1997; Grubler, 1998; Grubler et al. 1999; EPRI, 2011; Nakata et al., 2011). The current capability development effort is a new research frontier because it will incorporate time delays, technology readiness and non-technical barriers such as the integration with existing regulations and market-related infrastructure. The challenge will be to incorporate the correct engineering, regulatory and market variables. Without incorporating these aspects, the forward projection of technology readiness for a low carbon future may be highly uncertain. This capability is a true market penetration development effort based on both engineering (e.g., building the technologies in time to meet market demand) and regulatory (e.g., supporting policy) goals.

*1.4 A Tier-Priority Analysis Framework*

Prioritizing energy technology deployment goals according to a tiered structure gives the interested systems analysis modeler the ability to compare market diffusion across technologies within a given market using both traditional metrics (e.g., \$/MWh, tonnes/$CO_2$ emissions, dispatchability metrics) with non-traditional ones (e.g., political and social acceptability as they relate to time delays for deployment).

Using the classic Maslow's hierarchy of needs framework, Frei (2004) introduced the notion of energy policy needs. Access to basic energy services and then supplies of those services are two of the pillars of modern industrialized countries. Only after satisfying these very basic energy needs may other factors enter into consideration including the cost of those energy services and supplies, the use of these supplies and resources (e.g., substitutes and internalizing externalities), and social acceptability. Figure 2 illustrates the basic energy policy needs pyramid developed by Frei (2004).

[Figure 2]

The work presented in Figure 2 only adds to the new framework presented here by integrating the TRL and time delay methods within a hybrid and novel tier-priority framework based on the notion of a Maslow's hierarchy of needs pyramid.

## 2. Modeling a Technology Readiness Level (TRL)

The National Aeronautics and Space Administration (NASA), Department of Defense (DoD) and many other interested agencies and institutes use a metric known as the Technology Readiness Level (TRL). They use this metric to assess the maturity of a technology within the research spectrum from the conceptual stage to being application-ready. NASA largely pioneered the concept of quantifying the maturity 'stage' of a technology to assess how ready any new technology (or systems) may be for field deployment (Colladay, 1987; Mankins, 1995; Mitchell et al., 2006, Mitchell, 2007; Clay et al., 2007). Table 1 introduces one of the earlier versions of the TRL.

[Table 1]

Much of the technological innovation literature points towards research, development and demonstration (RD&D) (or research and development (R&D)) funds as the driving force behind the innovation engine.[2] Several approaches model the direct, or often indirect (e.g., through another sector of the economy or result of feed in tariffs or similar mechanisms) influences of energy technology RD&D (Sagar and van der Zwaan, 2006; del Rio and Belda, 2012; Kobos et al., 2006; Taylor et al., 2005).

Without funding, having meaningful impact for change (e.g., to reduce $CO_2$ emissions) in the scientific and subsequent public community may be difficult. Therefore, RD&D funding will be

[2] The authors acknowledge the difference between research, development and demonstration (RD&D) and research and development (R&D) in the literature, and in applied areas. For the sake of the TRL and related modeling discussed in this analysis, they will be considered to be interchangeable since development and demonstration could be considered similar in spirit up to a point as they relate to the goal and terminal TRL level of 9 representing a successful and operational technology. Additionally, much of the innovation-related literature used the term R&D until approximately the 1990s when RD&D became a more descriptive term applied in the similar literature.

used as the underlying driving force to move a technology from one TRL level to the next. It is important to note that moving from one TRL level to the next may not require a constant set of criteria. For example, in a hypothetical case, moving from a TRL of 1 to 2 may require $10 million and 2 years, but moving from a TRL of 2 to 3 may require $20 million and 3 years and so on. The specific funding level and timeline required to progress between the levels within the TRL framework should be technology-specific and adjustable according to the cost, time and related, specific performance and cost requirements criteria.

## 3. Modeling a Regulatory Readiness Level (RRL)

Without regulatory support or in the face of political resistance, a technology with the highest TRL level possible may still not be able to enter the market. This is due to the technology's access to the regulatory process, security of regulatory support (e.g., political capital), the effectiveness of that regulatory support to deliver meaningful legislation to support the technology (e.g., writing supporting legislation), the idea of 'do no harm' by introducing the technology in terms of environmental, cost or security, and finally the ability to pass legislation (or reduce resistance). These factors represent the core factors underlying the Regulatory Readiness Level (RRL).

In many instances, a new technology may require that supporters gather the regulatory support to introduce it into an existing market. In many ways, this is similar to understanding the rules of a game of chess that is already underway. The technology supporters may make their next move, but only within the constraints of those pieces already in play and the existing rules of the game. In the many options available to the technology supporter, there is a clearly defined way to win the game in a few short moves. However, many options require an extremely complex set of moves to increase the chances of winning – which is anything but certain. With a regulatory framework, there exist certain sets of legislation (potential rules of the game), and other competing technologies that may have political support for their technologies. New players may threaten the competing technology's existing secured access to the regulatory process and political acceptability (e.g., those with existing subsidies, those with a socially-acceptable quality, etc.).

It is important to also note that not all technologies can or will follow this pathway toward larger market adoption. Technologies that require high amounts of upfront capital (financial, human, physical, etc.) and game-changing, fundamental RD&D for *invention* (e.g., developing new biologically-based systems for more efficient algal-based biofuels) to produce the first item may take many more years to climb the initial technology readiness levels than a less capital intensive *innovation* (e.g., building and commercializing within the existing science and engineering to enhance the efficiency of current applications – such as more efficient blades for wind turbines or lower emissions from existing coal-fired power plants due to retrofits). Other examples may include comparing a new company producing electric vehicles with a new software firm that certainly have vastly different business plans due to the nature of the product, as well as the culture in which the technology is to be marketed (Chang, 2010; Westjohn et al., 2009; Mutula and van Brakel, 2006). The subsequent regulatory barriers may also be vastly different between the applications of competing or complimentary technologies within the same market, or if they are in different market applications all together.

Having technologies develop in the laboratory in parallel with developing regulations to guide those technologies in the marketplace can be mutually beneficial. Without the regulatory push, many technologies may not be adopted in the marketplace due to higher costs relative to not adopting those technologies. The Sulfur Oxide ($SO_x$) and Nitrous Oxide ($NO_x$) air regulations of the 1970s and 1980s, for example, progressed largely in parallel to the technology development (intentionally or otherwise) such that by the time the scrubber technology was ready to deploy to the marketplace (e.g., existing coal-fired power plants) the regulations were starting to enforce the change to lower emissions (Taylor et al., 2005; Rubin, 2012; Rubin et al., 2012). Thus, the regulations helped the technology find a secure market, and the technology helped the regulations meet its goals – to reduce acid rain pollution.

These lessons can also be extended to potential $CO_2$ management policies on existing fossil fuel-based power plants. A substantial challenge to developing a meaningful regulatory readiness level is to account for the uncertainty associated with $CO_2$ management policies throughout countries and regions looking to plan, manage, and ultimately reduce their $CO_2$ emissions (Markusson and Haszeldine, 2009). The central point here is to highlight how energy technology spillover and adoption are often strongly guided by the substantial oversight and regulation pertaining to the application of the technology (Cowan and Daim, 2011). It is for this very reason that in addition to technology readiness levels, there is a need to develop a regulatory readiness level quantification of these factors.

### *3.1 Access to and Understanding of the Regulatory Process*

Throughout the last several decades in many developed countries of the world, the focus of energy technology policy changed from energy access, to affordable energy, to low $SO_x$ and $NO_x$ emissions, to the post-Kyoto Protocol negotiations transition with a focus on lowering $CO_2$ emissions. These transitions were either led by, or followed, salient energy regulations or interests to institute the change. During the transition periods just before, and after these policy goals changed (mandatory or voluntary), a large degree of regulatory uncertainty tried to focus on the 'best' manner to approach, address directly, or address after the fact from the perspectives of the technology adopters or suppliers. A key challenge is to understand 'the rules of the game' such that the formal and informal institutions with a society and its respective market conditions are well understood to the point of reducing these uncertainties (Mitchell and Woodman, 2010; Negro et al., 2012; Rehman et al., 2012).

### *3.2 Security of Policy Certainty*

Beyond understanding the regulatory process it is paramount the business community have a large degree of relative certainty on the staying power of legislation, favorable or not, to new and innovative energy technologies. The challenges seen since the 1980s in the California wind energy industry, for example, saw dramatic swings in production tax credits. The result was a fragmented and often poor performing deployment of specific wind turbine technologies in an effort to capitalize on the production tax credits before they expired (Asmus, 2001).

However, from the 1990s to the early 2000s, substantial installations in wind energy have been seen throughout the world. In particular, 90 gigawatts of world generating capacity were installed in 2007 representing nearly 50 time as much installed capacity as in 1990 (OECD/IEA, 2008).

Uncertainty in the future climate policy may also lead to a ‘risk premium’ in the electricity markets. This premium may increase electricity prices for coal and natural gas-based power systems on the order of 5 – 35% (or more) in the face of potential $CO_2$ capture and storage (CCS) policies (Blyth et al., 2007). Similarly, a risk premium may be demanded of the consumers in an effort to pass through the cost of supply or smart grid or other new technology investment return in the face of additional regulatory uncertainty (Agrell et al., 2013; Jasmasb and Pollitt, 2008). The degree to which the premium passes to potential consumers is, however, highly dependent upon country-specific innovation systems. That is, in some countries the premium is absorbed via governmental-support for high-risk, high-reward energy systems, whereas in other countries this may not be the case (Vasudeva, 2009).

### *3.3 Policy Effectiveness*

To determine how effective a policy may be before implementing it can prove challenging. While the desired effect of a policy may be borne out in time, there can be substantial unintended consequences or elements contributing to the ineffectiveness of the policy in the years following implementation.

When determining the effectiveness of a policy focused on energy systems, it is often subject to one’s viewpoint. From an investor’s point of view, such as venture capital firms and private equity funds, the architecture of a policy and its ability to move past potential regulatory challenges may be seen as favorable (Burer and Wustenhagen, 2009). The ability of ‘market pull’-type of policies, such as production tax credits (PTCs) strive to increase demand in the marketplace for new technologies and provide incentives for users to adopt them. These policies are often compared to ‘technology push’ policies such as governmental or private RD&D funding to ultimately provide the supply of technology to the marketplace. Policies that may be considered ‘technology-push’ include government demonstration grants, public RD&D, grants, investment subsidies, private RD&D, tax breaks for entrepreneurs or investors, incubators, government investment in private venture capital, soft measures of support and government venture capital funds (Burer and Wustenhagen, 2009). Policies that may be considered ‘market-pull’ include feed-in tariffs, reduction of fossil-fuel subsidies, technology performance standards, residential and commercial tax credits, renewable fuel standards, $CO_2$ trading, public procurement, production tax credit, $CO_2$ tax, renewable portfolio standards, renewable certificate trading and clean development mechanisms (Burer and Wustenhagen, 2009). These types of policies strive to move the technology past the ‘valley of death’ where technologies may not progress successfully from the laboratory to the marketplace (Grubb, 2004; Weyant, 2011; Burer and Wustenhagen, 2009).

The effectiveness of a policy will be determined by the region and type of energy technology being assessed. For example, renewable portfolio standards (RPSs) in states across the U.S. may be very successful due to a supportive legislative and economic climate (e.g., Texas deployed 915 megawatts (MW) of wind in 2001 alone, doubling the projected RPS for that year) or challenged due to less favorable installation conditions (Carley, 2009). This may be due to whether the recipient of the RPS is an investor-owned or public utility (Delmas and Montes-Sancho, 2011) or in other instances, if a favorable regulatory environment or 'innovation system' exists (Jacobsson and Bergek, 2011). In these instances, the installed megawatts or power produced per policy is a key metric of success. In other instances, the cost of the policy instrument relative to the return on the energy project's lifetime impact may be the key metric of success (Lund, 2007).

Reducing the cost of energy systems can present an undesirable effect. When the cost of energy (and other types of resources) decreases, there may be a trend to use more energy due to its then lower cost. This type of 'rebound effect', also known as the Jevons paradox, can mitigate energy policies seeking to reduce $CO_2$ emissions, fuel consumption or increase efficiency (Jevons, 1866; Stepp et al., 2009; Bertoldi et al., 2013). This, along with a potential mismatch between the challenges associated with adopting a policy and its perceived effectiveness presents a policy dilemma when looking to convince others to adopt effective policy tools (Wiener and Koontz, 2012). This discussion leads into the notion that policies should, at the very least, 'do no harm'.

### *3.4 Do No Harm*

Including and measuring the appropriate incentives for change and the results of those changes are paramount to constructing a 'successful' energy policy. For example, energy policies often focus on increasing the efficiency levels of the technologies (e.g., end use technologies by the consumer). The initial effect of this type of policy is to reduce the energy used by the consumer. However, the 'Jevons Paradox' may occur where more end uses such as additional driving with a more efficient vehicle or using more electricity across more (although more efficient) end use technologies has the net effect of increasing energy consumption (Bertoldi et al., 2013). Modifying the incentive structure to both increase the efficiency of the technologies, while also suggesting to the consumers to modify their behavior such as driving less or using less electricity overall may be achieved by using additional policy mechanisms. These mechanisms may include feed-in tariffs that are directly tied to the amount of electricity (or energy) used rather than the end use technology itself (Bertoldi et al., 2013). By not accounting for the 'Jevons Paradox', some energy policies' goals to reduce energy use could actually increase it over time.

Policies focusing on RD&D, climate change mitigation and market price management are areas where targeting the 'optimal' policy framework may not be attainable, thereby leaving many interested parties worse off than before the policy took affect (de Bruin and Dellink, 2010). Without the correct market policies in place, the improvements to new technologies through RD&D may not be realized. This may be due to a focus on reducing the shorter-term costs of electricity via deregulation, for example, rather than investing in new, more efficient technologies with more appropriate metrics (e.g., domestic, scale-appropriate and/or renewable sources of energy in the longer term) seen by a reduction in RD&D spending or an incorrect measurement of the research's impact metrics (Dooley, 1998; Kostoff and Geisler, 2007). Similarly, rate structure policies in the electricity sector provide a rich area to illustrate price-cap, feed-in tariff, the effects of deregulation within the U.S. electricity sector, and performance-based regulation among many as to the desired vs. observed (or forecasted) unintended consequences (Seeto et al., 2001).

An effect (or possibly cause in some cases) of these counterproductive results in one policy goal may be due to successes in another area. The lack of overarching policy goal integration between atmospheric emissions, water, land use, and other resources may contribute to policies failing to meet their goals, or achieving a lower possible success level than otherwise they might have (Murray, 2013; Delshad et al., 2010). Balancing these systems within a comprehensive (or more easily integrated) suite of policy tools may help meet several societal and therefore likely desired goals.

The often cited not in my backyard or 'NIMBY' influence towards citing new energy technologies (e.g., wind) may help or hurt the deployment levels for the technology. A key challenge is to address 'lock-in' not only from the technological perspective, but the social (and sometimes political) aspects of ways of thinking towards accepting new or innovative technologies (Wolsink, 2012).

### *3.5 Political (& Social) Acceptability*

A necessary factor to include in most energy development projects is the social and therefore political acceptability of the project. Externalities, cost overruns and unforeseen intergenerational effects are not usually included in the overall system's costs for energy-related projects (Carrera and Mack, 2010). In their work, Carrera and Mack (2010) developed a set of criteria by which expert elicitation metrics were collected to understand what factors may or may deserve additional analysis when looking to develop new (or continue) energy projects. These criteria included (1) continuity of energy service over time, (2) political stability and legitimacy, (3) social components of risk, and (4) quality of life (Carrera and Mack, 2010). The core purpose of their analysis was to focus on the social sustainability of energy technologies using these expert judgments resulting in clear differences in opinion across technologies according to the countries from which the experts come from. One key finding focused on how most experts found smaller-scale technologies such as photovoltaics and fuel cells to be viewed more positively due to their smaller ecological and societal footprint and compatibility with current infrastructure relative to larger-scale systems such as nuclear and coal power.

In another study, Strazzera et al. (2012) developed a Choice Experiment approach to identify the factors that may highlight any support or opposition to wind energy projects, and what monetary tradeoffs may exist between different attributes of these projects. Their key findings indicate stronger opposition to these projects may be encountered when individuals or groups feel strongly against the visual impacts from a project. The opposition may be even stronger in cases where a location may be associated with their identity as well. From these findings, the willingness to receive compensation to offset these impacts may be lower if their opposition is higher due to these factors. Additionally, developing these sites reduces the option value to not develop the project in the spirit of sustaining the local economy through other means such as tourism that may depend on visual appeal.

Through cases such as these, as well as other energy projects that may meet resistance from local or regional populations, it may follow that the political opposition (actors in the local or regional government) would in many instances also reflect this resistance (choice) of the people.

## 4. Modeling a Market Readiness Level (MRL)

A key challenge for any new technology to achieve substantial market share is to secure timely and deep market adoption. After a technology moves through the TRL levels of 1 – 9, and then successfully receives the regulatory permissions to enter the application space, the ability of the market to receive this technology hinges on its value and utility relative to other technologies. The value and utility can come in a variety of forms. The value of any product can, arguably, be transferred to the customer or entity that receives the technology. This can be in the form of higher performance, lower resource use, or lower costs. The challenge when moving from an 'early adopter' phase to a larger level of market penetration is to settle several characteristics of the technology and the market in which it is to compete. As outlined by Jeffrey et al. (2013), a few of these characteristics of a technology to achieve a higher level of market acceptance, and therefore adoption, include the following:

- Design variety and consensus – in the short run, the lack of a design consensus may inhibit learning and thereby the pace of development
- Parallel support for incremental and radical innovation
- Feedbacks between learning-by-doing and learning-by-research
- Shared learning for generic technologies
- Knowledge and technology transfer from other industries

Similar studies investigated the correlations between the life-cycle for a material and how energy technologies utilize specific materials as they transition between the Initial Stage, Lift off and Decay, Revival and Rapid Growth (along with the Valley of Death) and Survival Stage as the key stages of market diffusion (Connelly and Sekhar, 2012). The latter two stages are of particular interest to the MRL framework such that if a technology can survive the 'Valley of Death' and 'Survival Stage' in the market, it will likely have a place in markets to meet a demand for the technology.

Maier (1998) also investigates the stages of product diffusion from the perspective of three core stages; invention, innovation and diffusion. Along with these stages, the invention stage also has two sub-stages including the technical failure of the product which stops progress towards an application, and a case where the product's progress also stops due to insufficient economic success potential. The latter sub-stage is similar to the RRL spectrum presented in this analysis such that without sufficient regulatory barriers removed, or support given, a product may not appear to have any potential economically-successful pathway and the progress of the product stops. Additionally, the innovation description given by Maier (1998) is similar to aspects of the RRL as proponents for the technology look to garner support for the technology. The diffusion stage is similar to the MRL such that without economic success, the product's pathway within the MRL stops due to insufficient economic success while competing in the market place.

Research by Ford and Sterman (1998) highlights similarly-staged aspects of product development by developing and illustrating a systems model that includes four distinct development activities. These guiding activities include process structure, resources, scope and targets of a product's development.

### *4.1 Access to Market Base*

In order for a technology to be successful in a given market setting, the technology must have access to the market base and its respective applications. In select regions of the world, for example, many people do not have access to electricity or modern cooking technologies. This type of situation, known as 'Energy Poverty', is an extreme case of the lack of market access for very efficiency, yet expensive electricity producing or cooking technologies (Rehman et al., 2012; IEA, 2012). The point is, without sufficient market access, technologies that may seem vastly superior to others in one economic environment become effectively irrelevant to meet needs in other select regions.

Similarly, novel and relatively expensive electricity technologies that reduce $CO_2$ emissions such as coal-fired power plants with $CO_2$ capture and storage, and ultrasupercritical technologies may produce less environmental emissions, but may be unattainable to regions with limited funds to support existing or new energy infrastructure.

The market's rules also may inhibit or open access to broader technologies and intermediaries. In the U.S. natural gas industry, a substantial shift towards more open market access occurred in 1980s (De Vany et al., 1994). Additionally, technological lock-in due to large infrastructure requirements may also inhibit new technology from entering the marketplace (van der Vorren, 2012).

### *4.2 Security of Financial Capital*

As energy, and most other technologies mature through the TRL spectrum, it is paramount that demonstration cases prove their viability and showcase their expected performance in order to attract the attention of those institutions that finance and regulate power plants (Rubin, 2012; Rubin et al., 2012). Similarly, larger policy-driven approaches also require energy technologies to pass a set of performance criteria to attract and retain industrial partners working within a regulatory framework to support new and innovative energy technologies. For example, policies in select European countries may become the most valuable by reducing the administrative process to install new wind technologies. Alternatively, in the U.S., similarly attractive policy measures may focus on improving the regulations for grid access and focus on the income per kWh based on total production (Alic et al., 2003). RD&D funding, market diffusion and institutional learning however are all required in differing amounts within select market environments given regional and country-specific regulatory and resource requirements (Luthi and Prassler, 2011; Nemet, 2012).

### *4.3 Manufacturability*

The ability of the existing industry to manufacture the technology will have profound effects on how quickly the industry's supply can meet potential demand. Without sufficient manufacturing capability in the face of strong demand, a shortage may inevitably develop that will in turn drive prices up in the marketplace. However, if an industry (or single firm) is able to increase production within a timeframe commensurate with the growth in market demand then the technology may be able to meet demand thereby securing a more positive influence on the technology's 'inertia' from the consumer's perspective to address their given quantity demanded at a point in time (e.g., for select defense systems, meeting manufacturability deadlines may take precedence over low costs in the short run) (GAO, 2002). In the long run, the ability of a firm or industry to increase manufacturing capacity to a level required to meet market demand will help stabilize the technology's cost envelope and offer a competitive advantage in the marketplace relative to competing technologies offering the same (or similar) service.

[Figure 3]

### *4.4 Market Cost Competitive and Profitable*

New or competing energy technologies will fare better in the marketplace if they have a cost or utility (e.g., same electricity produced with less fuel use such as renewables, or a lower $CO_2$ or other emissions profile such as coal-fired power plants with capture technologies installed) advantage. When technologies are first introduced to the marketplace, they may be sold at a loss or less-than-optimal profit margin in an effort to secure market share. Figure 3 illustrates the cost-price-profit interplay as a new technology enters the market and progresses through different stages of the technology adoption similar to those used when describing the 'S-shaped' market adoption modeling in Figure 3.

Shorter-term profit may not be the leading initial goal of a firm looking to establish their technology's place in the early market when first introduced to a highly competitive market with close substitutes. Profit will come at a point when sufficient market share has been gained to then pass through the cost reductions seen in learning-by-doing, economy of scale effects and other cost-reduction measures working in concert with potential pricing schemes to maximize profits in the more stable, mature market.

### *4.5 Consumer Utility*

Understanding the most valuable timeline for not only new and innovative technologies is the key component to the value or 'utility' seen for customers (technology adopters). The consumer initially may ask, 'How is this new technology or innovation going to reduce costs or overall increase my welfare?'

## 5. Combining Technology, Regulatory and Market Readiness Levels

To illustrate the new TRM framework a model framework was developed using system dynamics (SD).[3] By developing the causal loop diagrams, along with a technology-agnostic working model, the framework presents the relative strength of select drivers underlying the proposed TRM framework. Using the system dynamics platform, amongst others, allows future modelers the ability to adopt the core components and overarching theoretical framework into their technology analyses. The core components can then be integrated into other IAMs regardless of the technology under consideration, and to fully account for dynamic time delays seen in the development, regulation and market adoption of new technologies.

The readiness levels are represented for the technology, regulatory and market via the relationship,

$$\boldsymbol{\rho_i} = \iint_{\mathbf{1},\mathbf{1}}^{\boldsymbol{l},\boldsymbol{n}} (\boldsymbol{\alpha_{i,j}} - \boldsymbol{\beta_{i,j}})\,\boldsymbol{dt}$$

where $\boldsymbol{\rho_i}$ is the readiness level type $\boldsymbol{i}$ where $\boldsymbol{i}$ =*TRL*, *RRL*, *MRL*, $\boldsymbol{\alpha_{i,j}}$ is the rate of increase for $\boldsymbol{i}$ where $\boldsymbol{j}$ represents the readiness level type-specific driving units for the TRL, RRL and MRL of USD per year, political traction unit per year, and investment unit per year, respectively, $\boldsymbol{\beta_{i,j}}$ represents the rate of decrease for $\boldsymbol{i}$ given $\boldsymbol{j}$, $\boldsymbol{l}$ represents the number of levels readiness level type, and $\boldsymbol{n}$ represents the number of technologies in the TRM framework at any given time. The latter variable $\boldsymbol{n}$ allows one to compare numerous technologies to one another at the same time within the TRM framework. This allows for a side-by-side comparison on which technologies vying for a similar market space may achieve market acceptance before the others, or by a given time that the technology may address the aspects of a policy goal (e.g., to have technology be 'market ready' by a given year).

Figure 4 illustrates the underlying theoretical framework presented in equation 1 of the new TRM framework using the familiar 'pyramid' design and TRL lexicon. The technology readiness level, for example, is based on standard methods utilized in the research community to assess the maturity of a given technology. The regulatory and market readiness levels adopt this format to help quantify the factors that influence whether or not a given technology, even at the highest and most mature stage of the TRL, will have the political (regulatory) capital and appropriate market acceptance criteria available to become a commercial and/or widely applicable success.

[Figure 4]

[3] The model framework developed in such a manner that it can be used in other modeling efforts where appropriate such as those described in Pickard et al., 2009; Malczynski, 2011; Kobos et al., 2003, 2006, 2011, 2013, 2014.

## 5.1 Readiness Level Modeling Description

Moving the TRM framework from the theoretical to operational stage in a SD model, we begin by developing a causal loop diagram (CLD) to set the direction of the influential drivers for each readiness level. Using the CLD tools presents a unique and flexible framework to illustrate the underlying architecture of the TRM framework. Similar approaches have been used for technology adoption and policy analysis by Stepp et al. (2009) and Kumar et al. (2010). Each level within the readiness levels (TRL, RRL, MRL) represents a type of stock account. To move from one level to the next, a core driver for each readiness level must flow into these stocks. As mentioned previously, the flow for the TRL, RRL and MRL is USD per year, political traction units per year, and market units per year, respectively.

The readiness level threshold and increase for a technology to achieve within the TRL, RRL an MRL CLDs shown in Figures 5, 6 and 7 are represented via the relationship,

$$\boldsymbol{\rho_i} = \begin{Bmatrix} \boldsymbol{\rho_{i_t}} = 1, \ \ if\ \boldsymbol{\rho_{i_{t-1}}} = 0\ and\ \gamma_{i,j,t}\ >\ \gamma_{i,j} \\ \\ \boldsymbol{\rho_{i_t}} = 0, \ \ if\ \boldsymbol{\rho_{i_{t-1}}} \neq 0\ and\ \gamma_{i,j,t} > \ \gamma_{i,j} \end{Bmatrix}$$

Where $\boldsymbol{\rho_i}$ represents the current readiness level, $\boldsymbol{\rho_{i,t}}$ represents the current readiness level at a given time $\boldsymbol{t}$ in the analysis' run, $\gamma_{i,j}$ represents the driving unit threshold for each readiness level $\boldsymbol{i}$ using the driving unit $\boldsymbol{j}$, and $\gamma_{i,j,t}$ represents the current driving unit at time $\boldsymbol{t}$.

The ratio of actual readiness level achieved to the 'appraisal optimism'[4] (expected) level is represented via the relationship,

$$\frac{AT_{i,n,t}}{AO_{i,n,t}}$$

where $AT_{i,n,t}$ represents the actual level of the technology within the TRL, RRL or MRL, $AO_{i,n,t}$ represents the appraisal optimism level or expected level the technology should achieve within the TRL, RRL or MRL. Similarly, the decision to stop technology development within the TRM framework is driven by the relationship as,

$$stop\ technology\ development = \begin{Bmatrix} 1, if\ \dfrac{AT_{i,n,t}}{AO_{i,n,t}} < desired\ ratio_{i,n,t} \\ \\ 0, if\ \dfrac{AT_{i,n,t}}{AO_{i,n,t}} \geq desired\ ratio_{i,n,t} \end{Bmatrix}$$

Figure 5 illustrates the CLD for the TRL.

[4] Term 'appraisal optimism' adapted from Jeffrey et al., 2013.

[Figure 5]

The TRL CLD begins with TRL level 1, the earliest stage of at technology's development. As resources such as R&D and time are devoted to the technology (R&D activities for development of a technology) an increase in this variable will increase the 'progress on TRL for a specific technology' to move from one level to the next.[5] As the technology's TRL increases from, 1 to 2 for example, if it meets the 'ratio of actual to expected progress for a specific technology' which should decrease as the technology's research and is deemed to be making progress relative to what was expected (e.g., enough breakthroughs to increase performance, decrease cost, etc.) then this is a reinforcing loop fed by the 'expected progress for a specific technology (appraisal optimism)'. An increase in this ratio, representing good technological progress, leads to potentially more funding by securing additional 'money invested in R&D' if the progress exceeds the threshold given by investors to support the R&D effort via the 'threshold ratio for progress for a specific technology'. Ultimately, this positive feedback loop provides an increasing (or stable) funding source to raise the TRL from 1 to the terminal level of 9. Conversely, if sufficient progress is not made on the technology's R&D from the perspective of the investors (also seen as the researchers were too optimistic) this cycle becomes a negative feedback loop and the technology's funding is terminated and movement up the TRL spectrum stops.

Figure 6 illustrates the RRL CLD and its components. The RRL CLD uses political traction units. These units are user defined, to represent the political support necessary to allow a technology to enter the marketplace. Examples in the electricity sector might include certification of the power generating technology's engineering, power purchase agreement regulations already in place, environmental impact studies or considerations, and many similar constraints. Increases in the U.S. in shale gas production over the last several years represent a good example to illustrate the regulatory hurdles that exist in some states (e.g., New York State's ban on hydraulic fracturing for natural gas) as compared to regulations that are more favorable to the technology (e.g., Pennsylvania allows the use of these technologies) (Richardson et al., 2013).

[Figure 6]

The CLD for the MRL, shown in Figure 7, differs slightly from the TRL and RRL. The MRL includes and additional feedback loop to include the potential for demand in the industry to be influenced by the desire (driven also by market incentives such as profits or regulatory decree) of the technology consumers to see a sufficient supply in the market to meet their demand.

[Figure 7]

[5] Note in each of the CLDs, that when an increase in a given variable leads to an increase in the subsequent variable, this is denoted by a plus (+) sign. Similarly, if an increase in a given variable leads to a decrease in the subsequent variable, this is denoted by a minus (-) sign.

Figure 8 provides a system boundary causal loop diagram for the TRM framework. In particular, it illustrates the dynamic loops that describe achievement of a final product achieving terminal readiness levels. This is achieved by meeting the 'desired readiness level' in each of the readiness levels. A key component and constraint of the CLD is the 'resource limit for technology development' that incorporates the drivers for each of the three readiness levels, as well as the notion of implied time limit to achieve one's ultimate 'desired readiness level'. The resource limit is often correlated to the difficulty of achieving each of the readiness levels. For example, introducing a retrofit technology within the existing energy infrastructure such as CCS or more natural gas-based systems may be easier than introducing entirely new power systems at scales unseen in the existing infrastructure such as hydrogen-based power. The degree of difficulty could be embedded within the existing regulations, standards or perceptions of the technologies by regulators. Ultimately, these factors are trying to minimize the 'gap in readiness level' reflected by the difference between the 'actual readiness level achieved' across the three readiness levels and the 'desired readiness level'.

[Figure 8]

## 5. Discussion

Balancing economic and energy demand growth in the coming decades will depend greatly on the policy goals under development, or set to take effect. Demand side management (e.g., technology efficiency and consumer behavior), early adopter credits, financial underwriting and similar catalytic measures may help with both 'technology pull' and 'demand push' strategies to introduce and increase the share of less resource-intensive electricity generating technologies. Examples of these include renewable energy sources like wind and solar along with natural gas turbines to help alleviate demand pressures on electricity supplies in the face of limited fuels (e.g., low-sulfur and other coal technologies, constraints on nuclear fuel in the short run, regional constraints on natural gas supplies) given $SO_x$, $NO_x$, $CO_2$ management and energy security goals (Banales-Lopez and Norberg-Bohm, 2002). It is essential to recognize that newer energy technologies may have vastly different 'energy service' characteristics that go to the very heart of 'value' to the consumer. Trading one energy insecurity for another and increasing costs (and likely price) could, in some instances, make renewables for example, a less attractive, secure or economically-efficient solution to improving upon the cleanliness of other fuels and power options that provide energy services. Additionally, one of the most important factors affecting energy transition forecasting is the timeline of interest. Changes over the short term (<10 years) may be politically-tractable in some situations due to electoral turnover, whereas the technical or ramp-up capability of an industry during this timeline may be challenging. Over the medium term (30 years), many changes can and have been implemented when faced with a substantial environmental and technical challenge (e.g., chlorofluorocarbons (CFC) limitations; mitigation of acid rain constituents from the power sector). Over the long term (>50+ years), many of the given truths in the development of infrastructure, the state of the world's energy resources, and societal preferences may change so drastically that many forecasts once deemed plausible become less relevant.

The TRM framework was developed to help address the question, 'To meet our desired technical and policy goals, what are the factors that affect the rate we must install technology to achieve these goals in the coming decades?' The TRM framework allows existing IAMs to quantify these points on how long technology diffusion may take when including the regulatory and market constraints along with the technology research and development process. Understanding the time required for a new or innovative energy technology to build a sufficient share of the market is directly linked to its ability to meet a given policy goal such as to lower energy costs, $CO_2$ emissions, and reliability metrics.

## 6. General Conclusions and Policy Modeling Implications

This analysis presents a new and novel framework as a first known attempt to quantify the time delays explicitly due to regulatory readiness and market readiness level perspective similar in spirit to the more commonly used technology readiness levels. The appealing aspect of this TRL, RRL and MRL framework and subsequent illustrative TRM model framework is its wide applicability to not only energy systems as they relate to a transitioning energy portfolio in the electricity sector, but to many types technologies in other sectors and applications. The research community that develops the integrated assessment models (IAMs), in particular, may benefit from this theoretical and applicable approach. The key benefits include integrating how the 'timing is everything' as to whether a technology will be ready for the marketplace in time to meet an overarching policy goal (e.g., technology involving $CO_2$ capture and storage from coal-fired power plants must be ready and deployed in a timely manner if certain levels of atmospheric $CO_2$ will stabilize by the policy's target date).

These results can be very case-specific and would certainly benefit by applying another level of uncertainty quantification throughout the potential to meet specific readiness levels within a given timeframe. However, applying the TRM framework more generally represents a large step towards quantifying these variables that are often difficult to explicitly quantify within the mathematical framework of IAMs.

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Figure 1

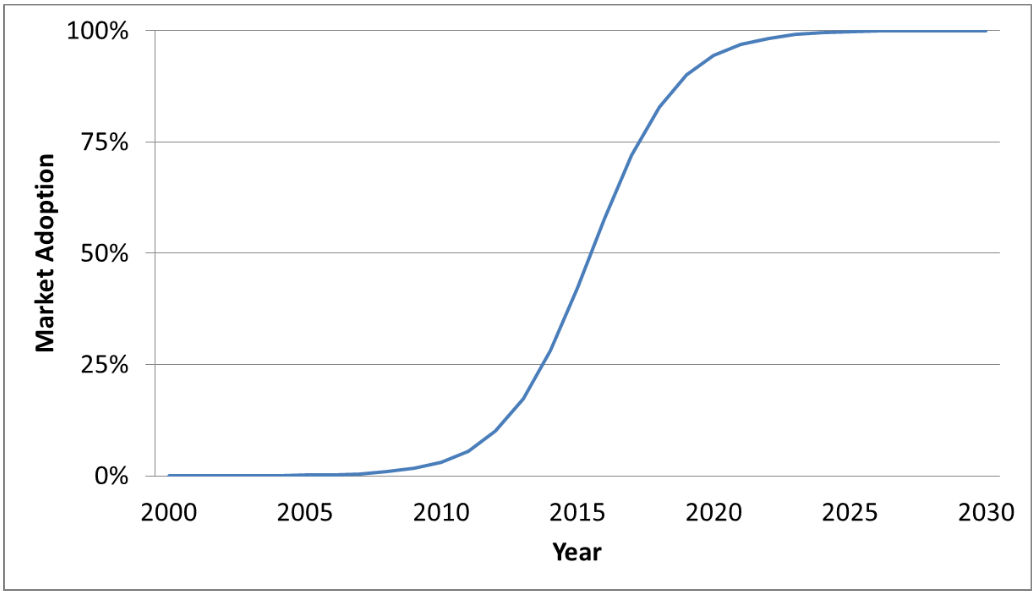
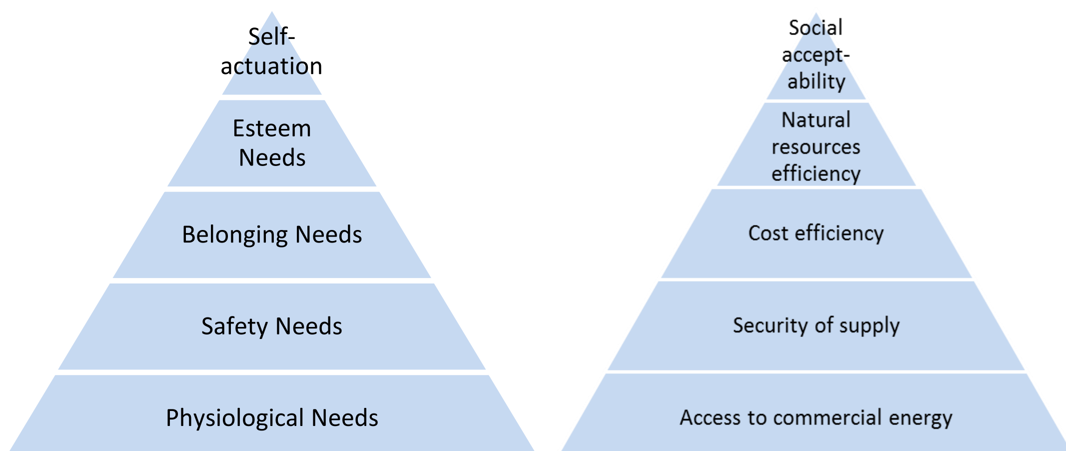



Figure 1. Market Adoption Modeling using an 'S-shaped' Trajectory over Time.

Figure 2




Maslow, 1954 Frei, 2004

Figure 2. Synthesizing Energy Policy goals with Maslow's hierarchy of needs (adapted from Maslow, 1954; Frei, 2004).

Figure 3

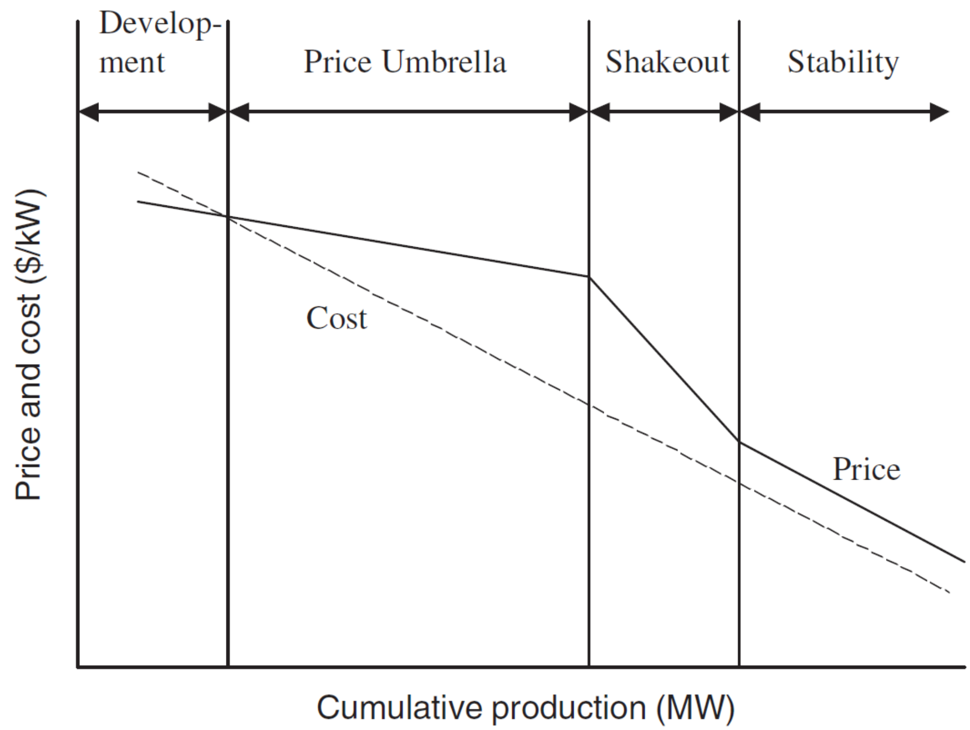
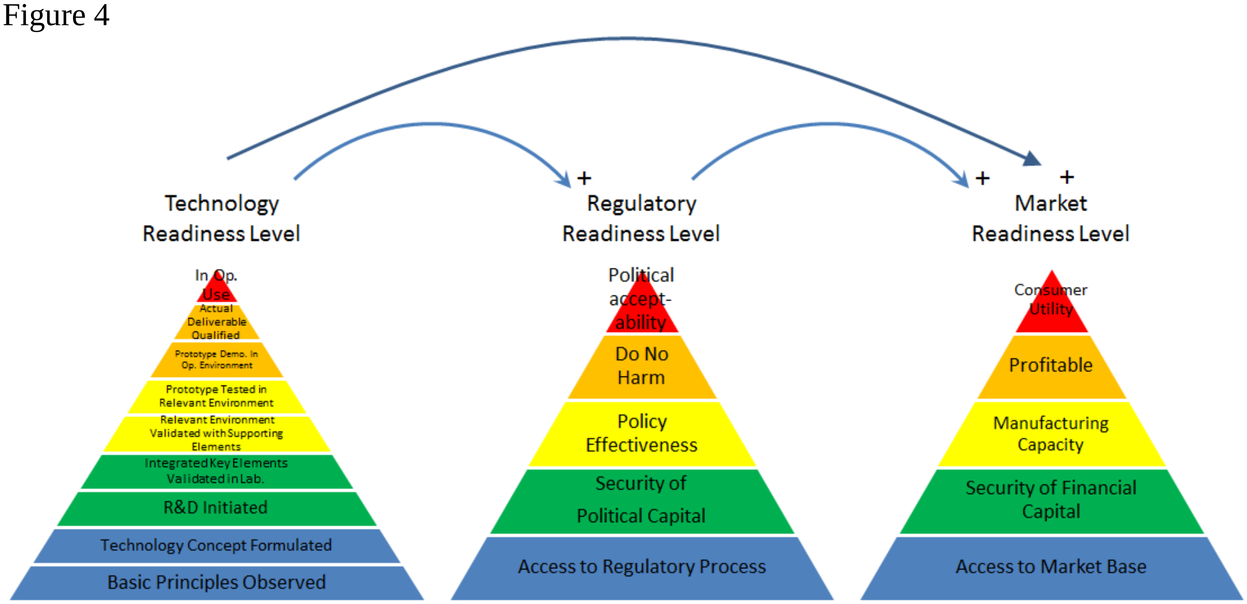



Figure 3. Production cost and market price for hypothetical energy technology systems (adapted from Boston Consulting Group, 1968; illustrated by Kobos et al., 2006).

Figure 4




| | | |
|---|---|---|
| **Technology Readiness Level (1-9)** | **Regulatory Readiness Level (1-5)** | **Market Readiness (1-5) Level** |
| **‘Can we build it?’** | **‘Can we accept it?’** | **‘Will they adopt it?’** |

Fig. 4. Technical Readiness Level (TRL), Market Readiness Level (MRL) and Regulatory Readiness Level (RRL).

Figure 5

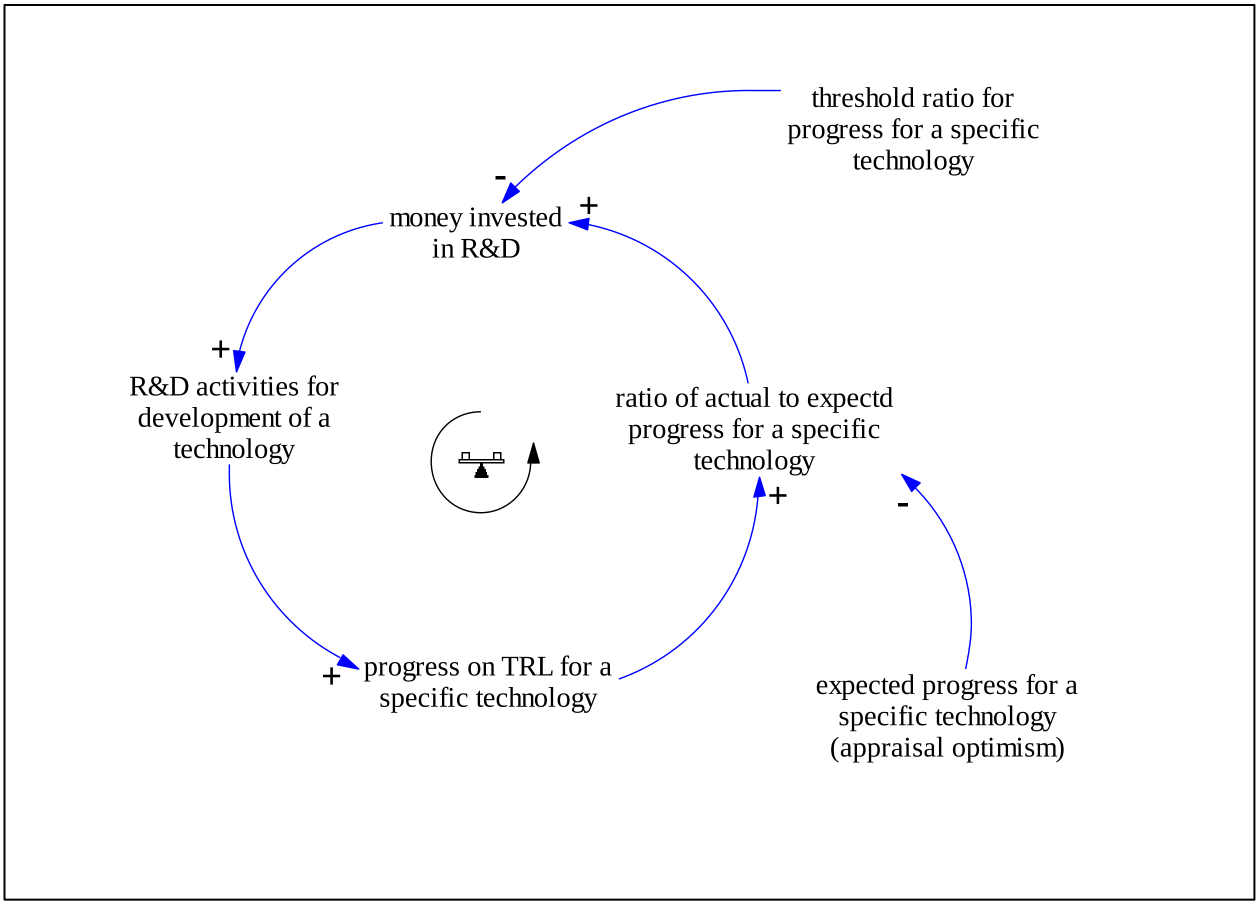



Fig. 5. Technical Readiness Level (TRL) Causal Loop Diagram Illustrating the Core Driving Force ($US invested in R&D).

Figure 6

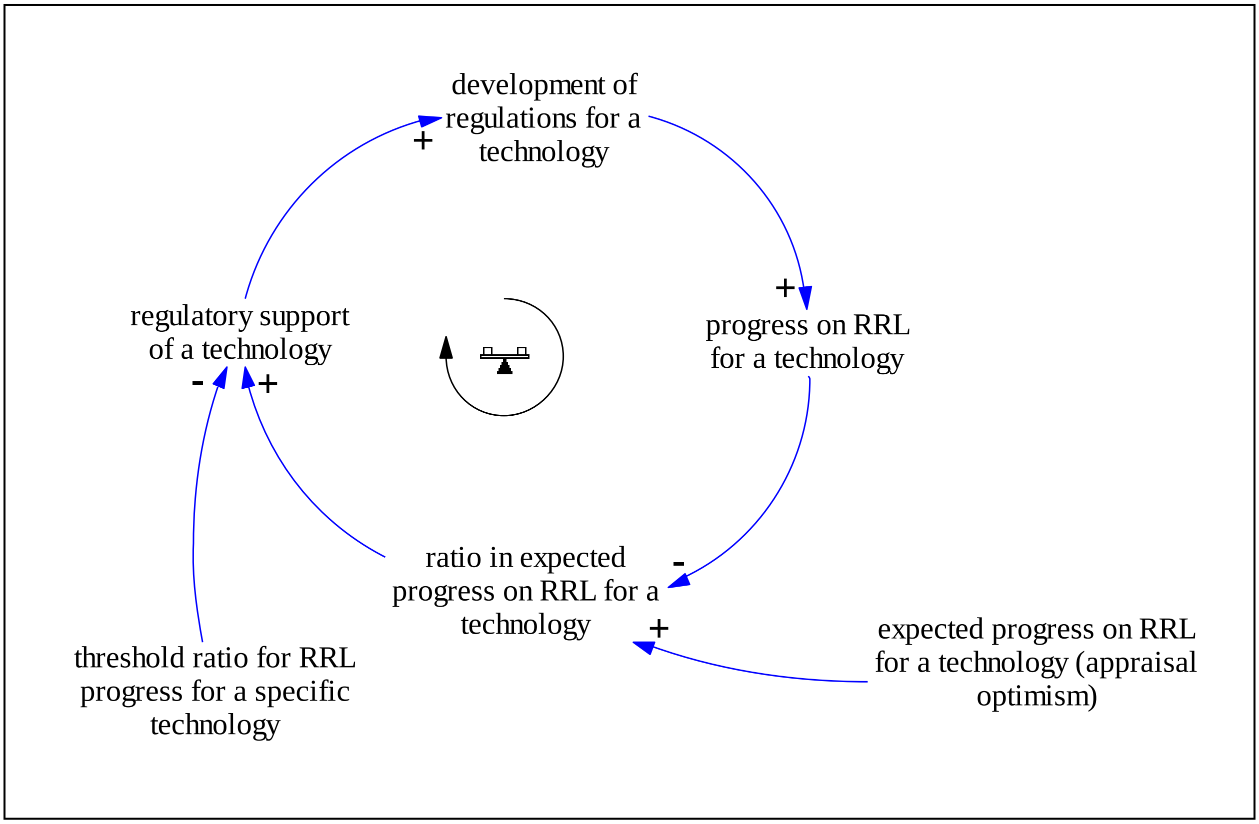



Fig. 6. Regulatory Readiness Level (RRL) Causal Loop Diagram Illustrating the Core Driving Force (traction unit).

Figure 7

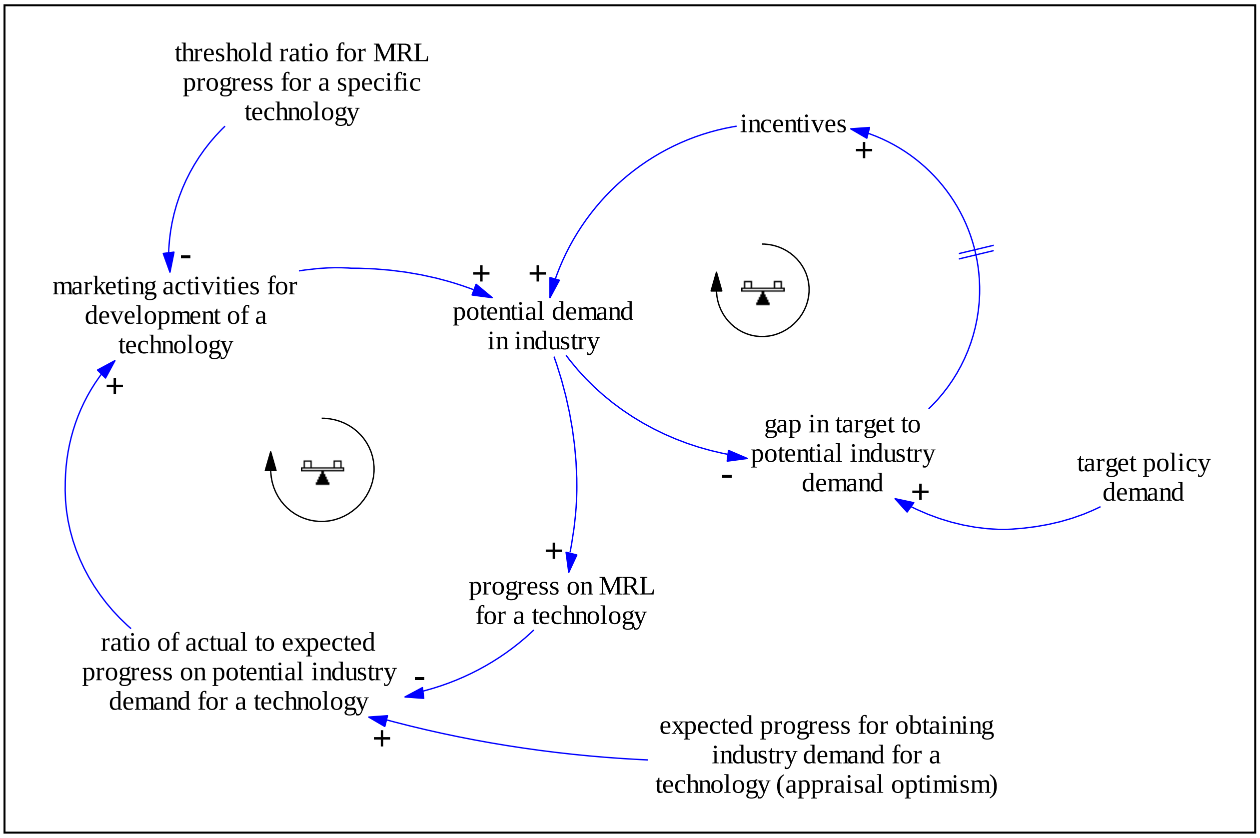



Fig. 7. Market Readiness Level (MRL) Causal Loop Diagram Illustrating the Core Driving Force (investment unit).

Figure 8

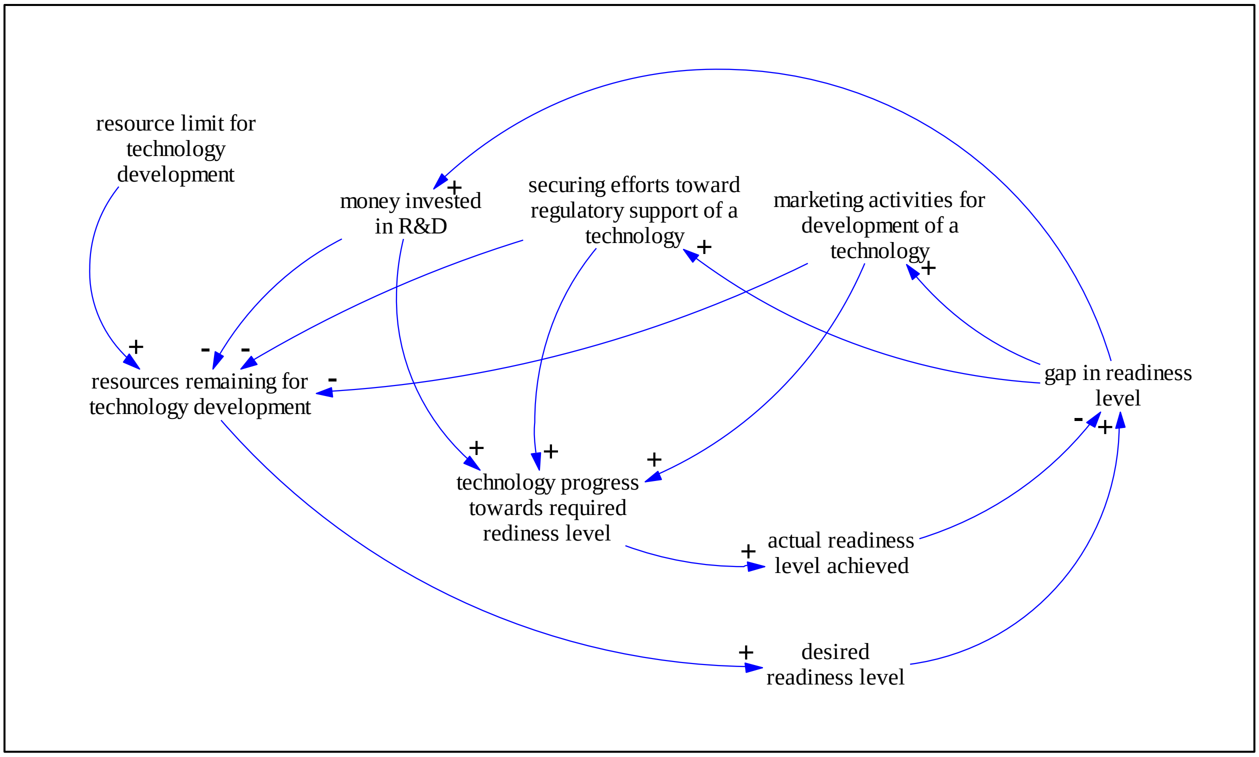



Fig. 8. Applying the TRM Combined Analytical Framework.

Table 1

**Table 1**

Technology Readiness Levels Summary by NASA (adapted from Mankins, 1995).

| Technology Readiness Level (TRL) | Description |
|---|---|
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of-concept |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in relevant environment |
| TRL 6 | System/subsystem model or prototype demonstration in a relevant environment (ground or space) |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and “flight qualified” through test and demonstration (ground or space) |
| TRL 9 | Actual system “flight proven” through successful mission operations |