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Timing is Everything: Along the Fossil Fuel Transition Pathway.

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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. Therefore, our research question is, '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?' Existing models do not include full regulatory constraints due to their often complex, and inflexible approaches to solve for 'optimal' engineering instead of 'robust' and multidisciplinary solutions. This project outlines the theory and then develops an applied software tool to model the laboratory-to-market transition using the traditional technology readiness level (TRL) framework, but develops subsequent and a novel regulatory readiness level (RRL) and market readiness level (MRL). This tool uses the ideally-suited system dynamics framework to incorporate feedbacks and time delays. Future energy-economic-environment models, regardless of their programming platform, may adapt this software model component framework or 'module' to further vet the likelihood of new or innovative technology moving through the laboratory, regulatory and market space. The prototype analytical framework and tool, called the Technology, Regulatory and Market Readiness Level simulation model (TRMsim) illustrates the interaction between technology research, application, policy and market dynamics as they relate to a new or innovative technology moving from the theoretical stage to full market deployment. The initial results that illustrate the model's capabilities indicate for a hypothetical technology, that increasing the key driver behind each of the TRL, RRL and MRL components individually decreases the time required for the technology to progress through each component by 63, 68 and 64%, respectively. Therefore, under the current working assumptions, to decrease the time it may take for a technology to move from the conceptual stage to full scale market adoption one might consider expending additional effort to secure regulatory approval and reducing the uncertainty of the technology's demand in the marketplace.

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1. INTRODUCTION

To address National Energy and Climate Security challenges by lowering carbon intensity for stationary power, it is vitally important to understand the speed at which new energy technologies replace older ones. Research projects that forecast technology transitions become suspect when they ignore or underrepresent the regulatory and market integration constraints. 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 simulation model (TRMsim) is a tool that describes the engineering and regulatory factors required to reach technological surety that can then be applied to energy security and CO_2 management goals in the coming years. Recent increases in the Corporate Average Fuel Economy (CAFÉ) vehicle fuel standard is a good example of the regulatory framework helping technology meet fuel economy goals. The technology, arguably, was ready or just about ready to deploy across the vehicle fleet, 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 fueling infrastructure – reducing this barrier to entry for widespread market adoption.

The same argument applies to U.S. electricity sector technologies about the importance of addressing regulatory barriers. This challenge spans beyond most governmental, academic and national laboratory's expertise (e.g., multidisciplinary). Without favorable regulatory integration factors, new stationary energy technologies such as enhanced installations of coal-fired power plants with CO_2 management technologies may never reach their full market potential due to recent large-scale, low cost domestic supplies of natural gas. Even with these factors in place (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 goals can be met. Therefore, the timing is everything for technology transitions in the marketplace.

1.1 Modeling Technology Transitions

This project brings a *new capability* to engineering-economic-energy modeling 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 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. The technical approach will develop in three distinct stages by addressing technological, regulatory and market factors built upon the research progress technique of the Technology Readiness Level (TRL). Interested readers should note there are many 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).

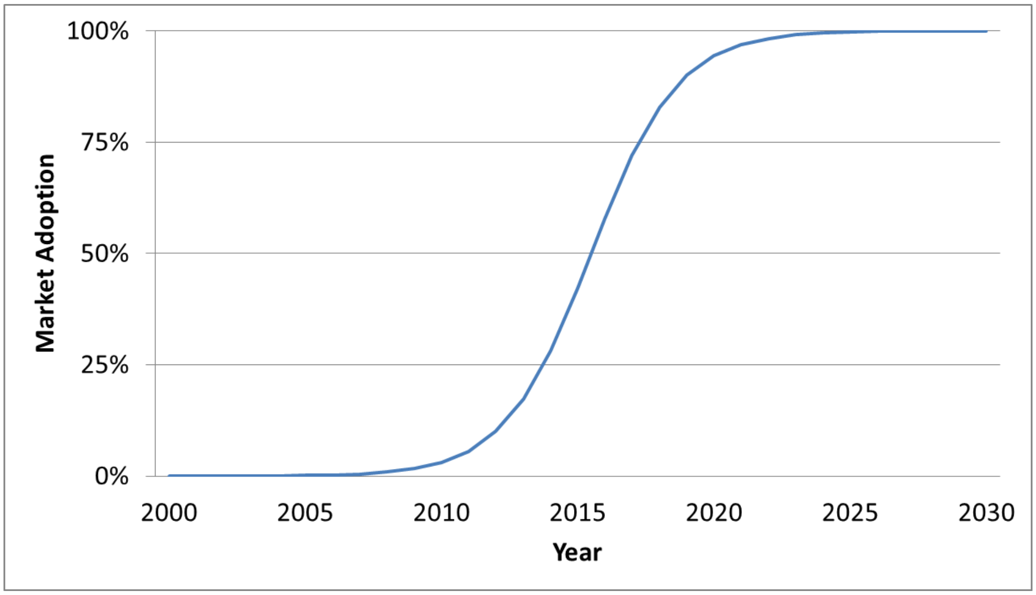

Figure 1. Market Adoption Modeling using an 'S-shaped' Trajectory over Time.

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 illustrated in Figure 1, this analysis develops three core modeling modules.

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 adoption.

Second, building from this information will help identify the Technical Readiness Level (TRL), Market Readiness Level (MRL) and Regulatory Readiness Level (RRL) for existing and new electricity technologies. Are CO_2 capture and storage (CCS) technologies 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 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 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?

Third, using these readiness level metrics, a systems insight capability model 'molecule' will be developed to illustrate how quickly these technology, manufacturing and regulatory TRLs must 'ramp up' to meet future CO_2 policy goals. A model 'molecule' is a self-contained model that is topic specific (e.g., to this TRL, MRL and RRL framework) while being generic enough to be applicable to a wide range of technologies and modeling methods via its underlying core components and theoretical underpinnings. Ultimately, this project draws lessons from the U.S. electricity sector as the initial example to illustrate 'timing is everything' when planning a future with (or without) fossil fuels.

Finally, synthesizing all of these efforts within the systems insight model 'molecule' tool offers substantial advantages over other engineering-economic-energy models. 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) using classic optimization or general equilibrium models are not flexible enough to integrate TRLs and (2) adopting TRLs for technology is not new, but utilizing the tiered framework to explore regulatory and manufacturing constraints is a completely new concept. This concept will identify the *value* of timeliness and interconnectedness within the economy for energy technology installations 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

Private industries, academia and many other national laboratories 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 with a multidisciplinary approach a unique opportunity. This opportunity presents itself to those with the ability to combine TRL, regulatory considerations and market assessment modeling to develop this capability that is currently lacking in the research community.

To provide some additional context, dozens of energy supply and demand forecasting models exist today, yet virtually none of them incorporate the evolutionary time delays and Technology Readiness Levels (TRLs) for *regulatory* and *market* forces to support technology manufacturing and adoption (Brown and Chandler, 2008; EMF, 2011). Incorporating the feedbacks seen in supply chain models in engineering-economic-energy models 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 in 1964. This was, of course, prior to the TRL approach applied to research and development (R&D) progress in the 1980s (Roberts, 1964; 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 this work, 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 aggressive levels of installing CCS technologies from virtually none on coal plants in 2020 to roughly 70% of them within a few decades. They assume an unconstrained technology build up and deployment rate 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, policy support or market conditions proxies or how this affects its 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 ramp up to their full potential). 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 regulation/legislation 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 (2012) forecasts nuclear power to expand in the U.S. around the year 2050. However, it is unclear if there is any domestic / international industry able to ramp up production of new energy plants 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 / 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).

The risk for this project is the inability to capture sufficient details in the electricity market's technology, market and regulatory readiness levels. However, the expected results, even if limited, will highlight where in the R&D planning process budget one should consider the overall impact of a technology / strategy to meet their policy goals. In this case, it is 'de-carbonizing' fossil fuels and the electricity portfolio overall. Therefore, this LDRD project will incorporate a true regulatory and market readiness level systems analysis tool capability that does not exist in the current modeling community.

1.3 Replacement and Turnover Time

Technology transitions take time; up to 50+ years for a full replacement of an energy technology (e.g., from 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). A core goal of this analysis is to integrate 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.

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).

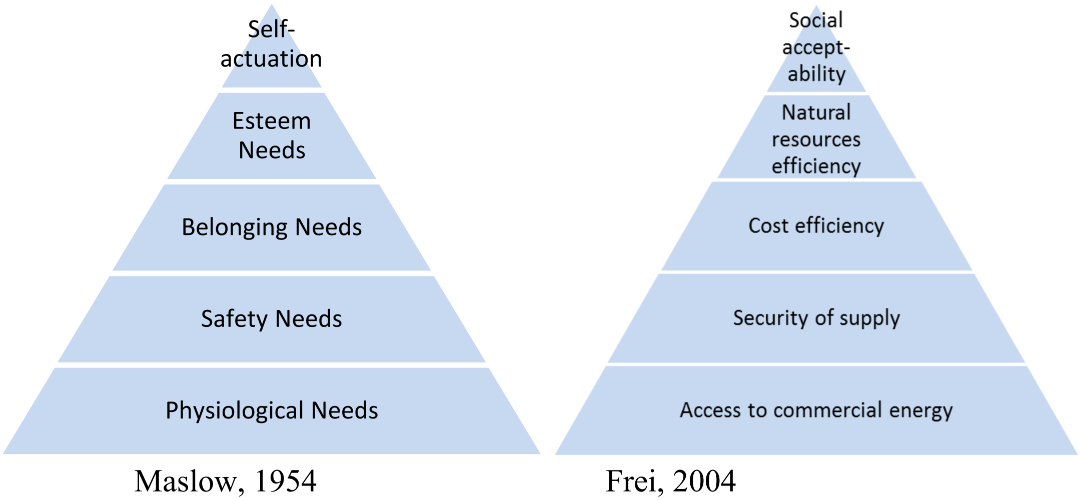

Figure 2. Synthesizing Energy Policy goals with Maslow's hierarchy of needs (adapted from Maslow, 1954; Frei, 2004).

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) to assess the maturity of a technology within the research spectrum from the conceptual stage to being application-ready. Much has been written on Technology Readiness Levels, and therefore this report will introduce the concept to the unfamiliar readers but leave additional, detailed explanations to other articles such as Colladay (1987) and Mankins (1995).

Over the last several decades, researchers at 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. 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

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.[1] 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, it may be difficult to have impact in the research community. Therefore, RD&D funding will be used as the underlying driving force to move a technology from one TRL level to the next. It is important to note that movement 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 cost $10 million and 2 years, but moving from a TRL of 2 to 3 may cost $20 million and 3 years and so on. The specific funding level and timeline required to progress between the TRL will be technology-specific and adjustable by the interested analyst.

3. MODELING A REGULATORY READINESS LEVEL (RRL)

Without regulatory support or in the face of political resistance, a technology with a terminal TRL level of 9 may still not be able to enter the market. This is due to several factors including, but not limited 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

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[1] 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.

ability to pass legislation (or reduce resistance). This represents the spirit of a Regulatory Readiness Level (RRL).

In many instances, it is necessary to have a technology's proponents gather the regulatory support to introduce a new technology in an existing market. In many ways, this is similar to understanding the rules of a game of chess that is already underway. The technology proponents may make the next move, but only within the constraints of those pieces already in play and the existing rules of the game. In many options 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 competitors that may have political support for their technologies. New players may threaten their already secured access to the regulatory process and political acceptability (e.g., those with existing subsidies, those with a socially-acceptable quality and thereby have political support).

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., biotechnology) 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 existing science and engineering to enhance the efficiency such as more efficient blades for wind turbines or lower emissions from existing coal-fired power plants due to retrofits). Other examples may include a new company to produce electric vehicles as compared to a new software firm 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 and the technology helped underpin the ability to meet the goals of the regulation: 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 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 – however preliminary it may be in the current literature.

3.1 Access 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 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 in the 1980s in the wind energy industry in California, 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, in 2007, 90 gigawatts of world generating capacity was installed 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 others this may not be the case (Vasudeva, 2009).

3.3 Policy Effectiveness

To determine how effective a policy may be before its implementation is challenging at best. While the desired effect of a policy may be borne out in time, there can be substantial unintended consequences or ineffectiveness elements in the years following implementation.

Determining the effectiveness of a policy focused on energy systems is subject to one's viewpoint of the market. 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 incentive for users to adopt them is 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. 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, 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 convincing policy makers 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

Political, economic and social factors both influence and are the result of energy policies that target technology innovation and deployment. While these factors do not necessarily inhibit one another, the magnitude of their influences may be greatly at odds.

One could argue the purpose of energy technology policies is to increase the benefits to each of these three (and likely other) factors. Externalities, those factors with influence but excluded from the benefit and cost calculations for these three core factors, may move the resultant policies towards these less desirable endpoints.

Along the lines of the appropriate metrics to include when assessing the results of energy policies, successful policies need not be large or complicated in spirit, but in actuality the multitude of interested parties (e.g., political, economic and social benefactors) should rightfully be included. Including and measuring the appropriate incentives for change and 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 driving more 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 such as 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 may 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 goal, 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 not matter 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 between technologies and 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 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 stage 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 the status quo become effectively irrelevant to meet specific needs in 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, matures through the TRL spectrum, it is paramount that demonstration cases prove their viability to perform as expected 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 for new wind technologies whereas in the U.S. similarly attractive policy measures may focus on improving the regulations for gird access and focus on the income per kWh based on total production (Alic et al., 2003). Policies that seek to promote technologies that reduce greenhouse gas emissions are also country and region-sensitive. Research, Development and Demonstration funding, market diffusion and institutional learning however are all required in differing amounts within select market environments (Luthi and Prassler, 2011).

4.3 Market Cost Competitive

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 1.

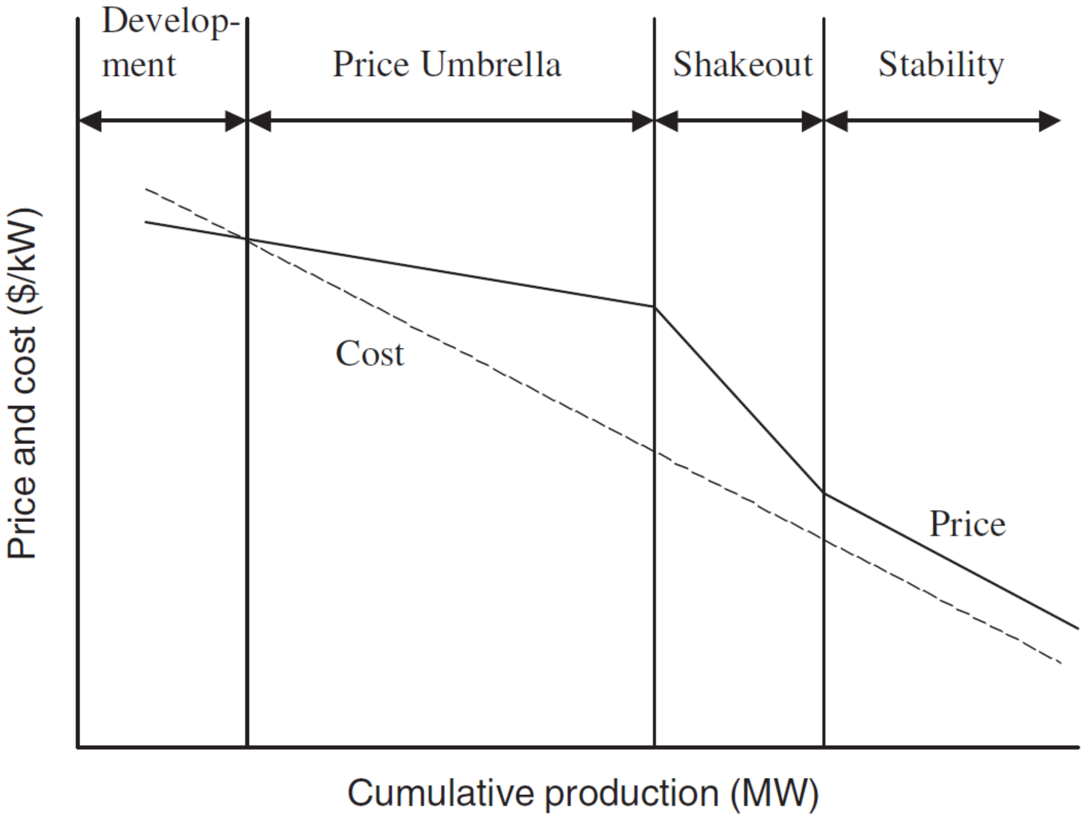

Figure 3. Production cost and market price for hypothetical energy technology systems (adapted from Boston Consulting Group, 1968; illustrated by Kobos et al., 2006).

4.4 Profitable

Technologies will progress through a period of time when first introduced to a highly competitive market with close substitutes, where profit may not be the leading initial goal of the firm. 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 market. Thus, a firm will look to achieve profitability for its technology, but it may take time.

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. THE TECHNOLOGY, REGULATORY AND MARKET READINESS LEVEL MODEL

The Technology, Regulatory and Market Readiness Level Simulation Model (TRMsim) integrates the technology-specific, regulatory constraints and required market conditions in a system dynamics (SD) model.[2] Building TRMsim using system dynamics allows future modelers the ability to adopt the core components / root insight equations and overarching theoretical framework into their technology analyses regardless of the technology under consideration (Appendices A and B). A large number of Powersim Studio models, for example, have been developed at Sandia National Laboratories and beyond that could benefit from the modeling tool developed for this project (Pickard et al., 2009; Malczynski, 2011).

Figure 4a illustrates the theoretical framework underlying the analysis of the technology, regulatory and market readiness levels. The technology readiness level, for example, is based on standard methods utilized in the research community to assess the maturity of a given technology. Building from this progressive, pyramid-shaped illustrative framework, the regulatory and market readiness levels adopt this familiar format in an effort to 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 capital and appropriate market acceptance criteria available to it to become a commercial and/or widely applicable success.

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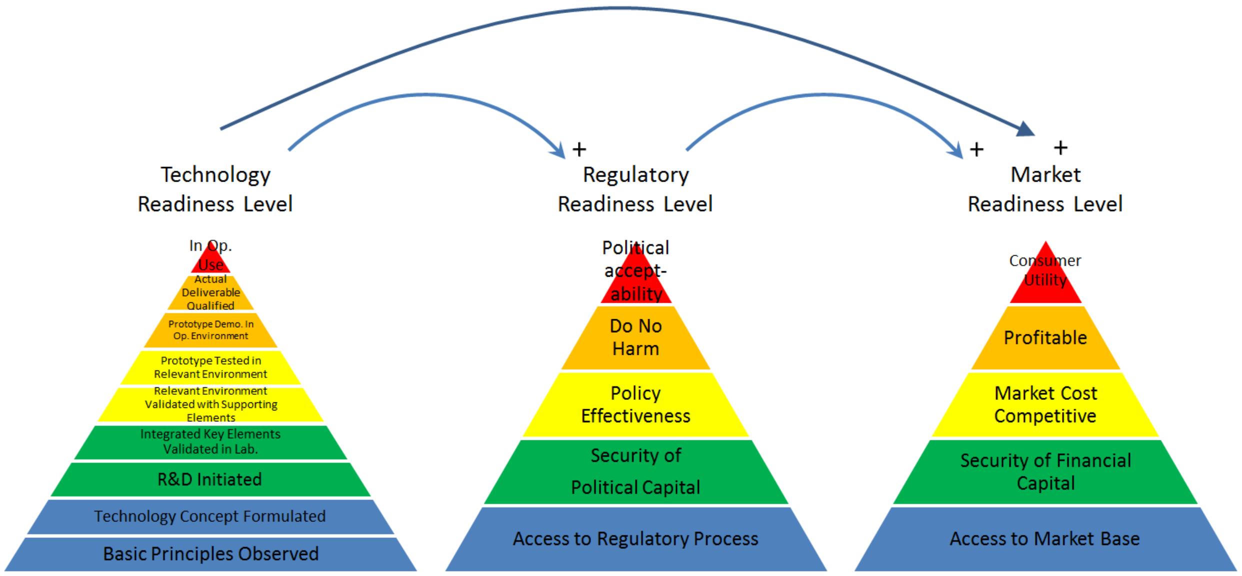
[2] Powersim Studio 9 was used to develop TRMsim. TRMsim developed in such a manner that it can be used in other Powersim Studio modeling efforts as a type of standalone ‘module’ or utilize the core components / root insight equations in other computer modeling platforms where appropriate.



Technology Readiness Level (1-9)
'Can we build it?'

Regulatory Readiness Level (1-5)
'Can we accept it?'

Market Readiness (1-5) Level
'Will they adopt it?'

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

Building on this proposed methodology, the next step is to translate this technology, regulatory and market framework into a system dynamics model. Developing a causal loop diagram (CLD) initially helps set the direction of the influential drivers for each readiness level. The core drivers of the CLD for the technology, regulatory and market readiness levels are $US, traction units, and investment units, respectively. These drive increases in the TRL (technology level), RRL (political unit) and MRL (market unit). Figures 4b, 4c and 4d expand upon the methodology developed in Figure 4a by looking to operationalize the methodology in a causal loop diagram (CLD) framework leading towards a system dynamics based model.

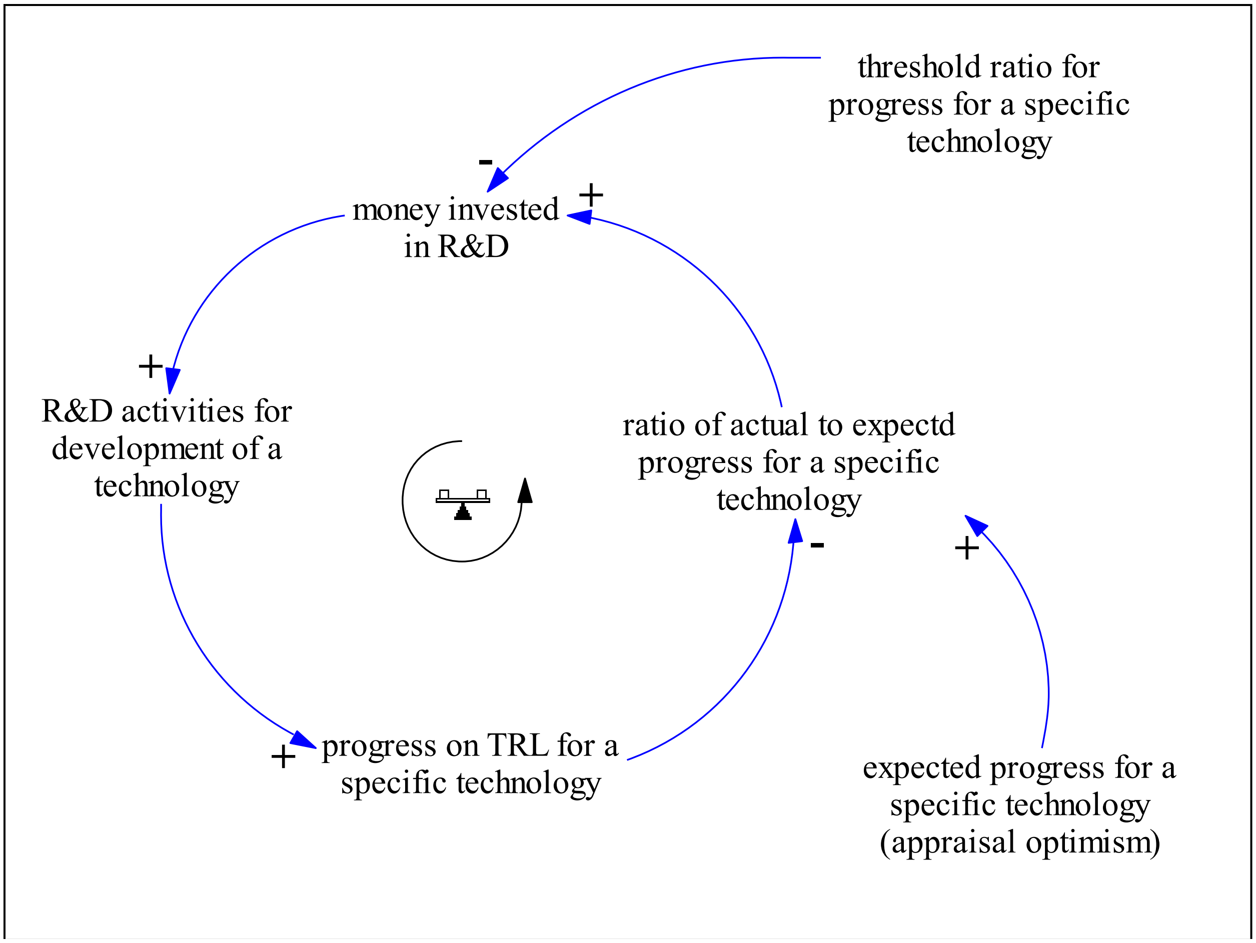


Figure 4b. Technical Readiness Level (TRL) Causal Loop Diagram Illustrating the Core Driving Force ($US invested in R&D).

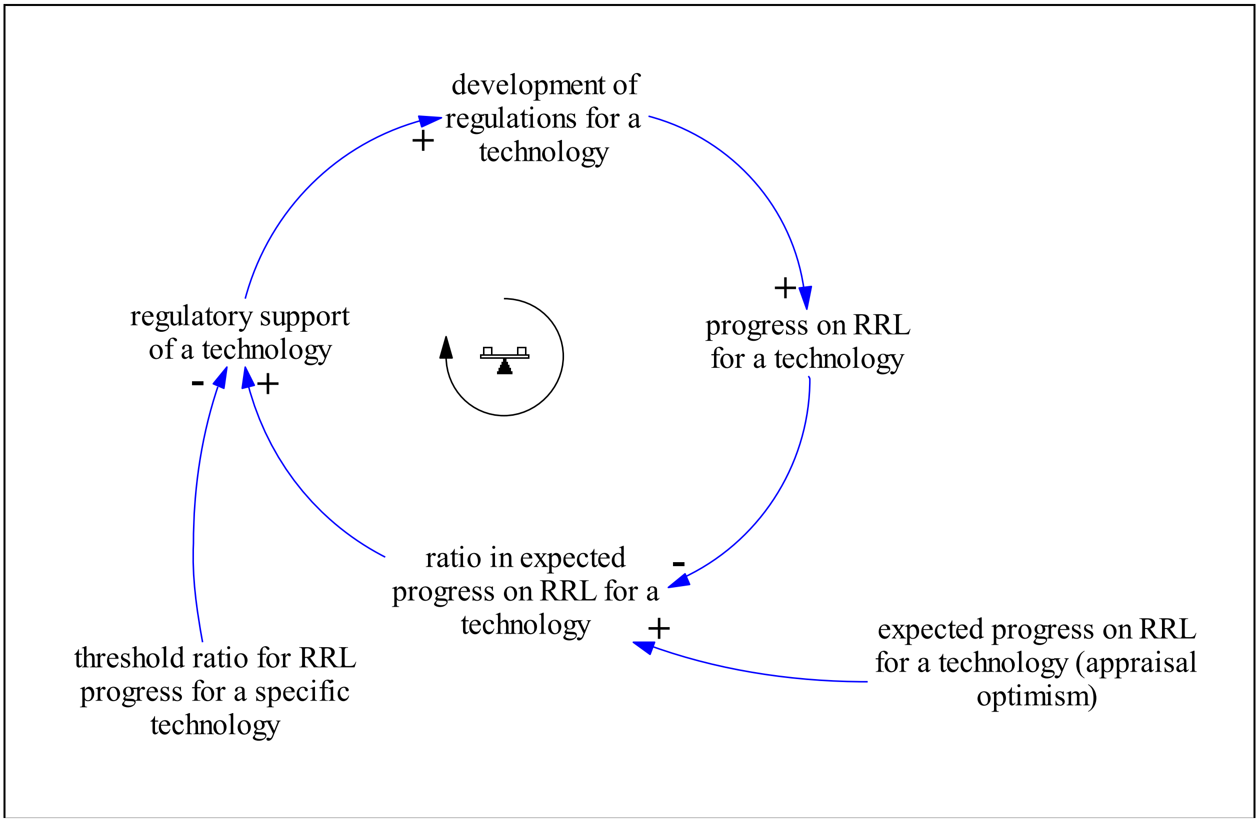


Figure 4c. Regulatory Readiness Level (RRL) Causal Loop Diagram Illustrating the Core Driving Force (traction unit).

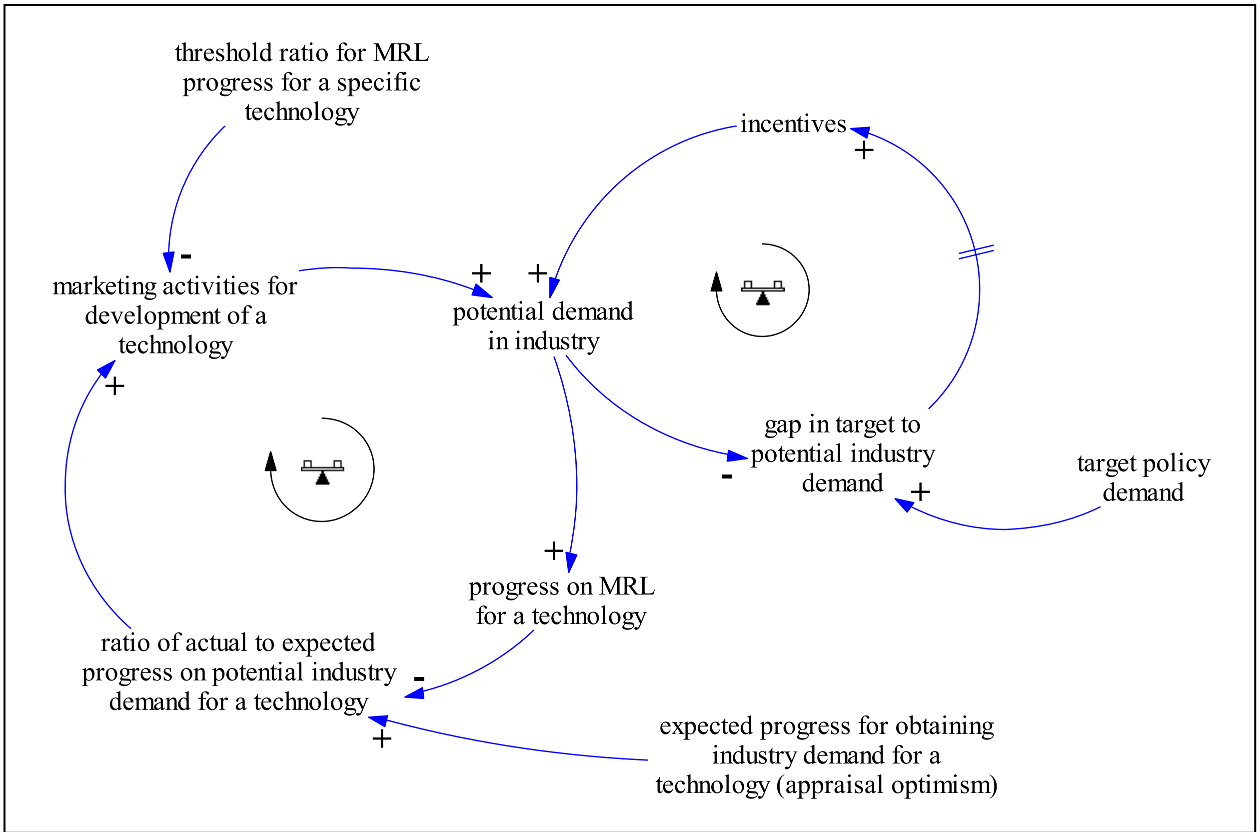


Figure 4d. Market Readiness Level (MRL) Causal Loop Diagram Illustrating the Core Driving Force (investment unit).

5.1 Module Development

Three readiness levels (RLs) were incorporated to represent the overarching structure and dynamic results to be developed. Next, the underlying drivers of each readiness level (RL) were developed. The drivers for the TRL, RRL and MRL were U.S. dollars to fund and drive research from the laboratory to the field, traction units of political influence and interest in the technology being investigated to model the support (or lack thereof) for a technology, and market investment units that serve as a surrogate for market share of the new technology relative to its competitors or the new use and influence of the technology in the market, respectively.

Figure 5 illustrates the main interface results screen of TRMsim. From the top of the figure on the upper left-hand side, is the technology option box. One of the key take away messages from Figure 5 is to note the time it takes for a technology (e.g., “Tech 1” in this instance) to first progress up the TRL, RRL and MRL at 9.5, 7 and 5.5 years, respectively. In short, it may take this technology, under these assumptions 22 years to move from the conceptual stage to market deployment as shown in the upper right-hand corner of the interface.[3] In this scenario, Tech 1 must progress and complete the nine stages of the TRL progression before moving on to the

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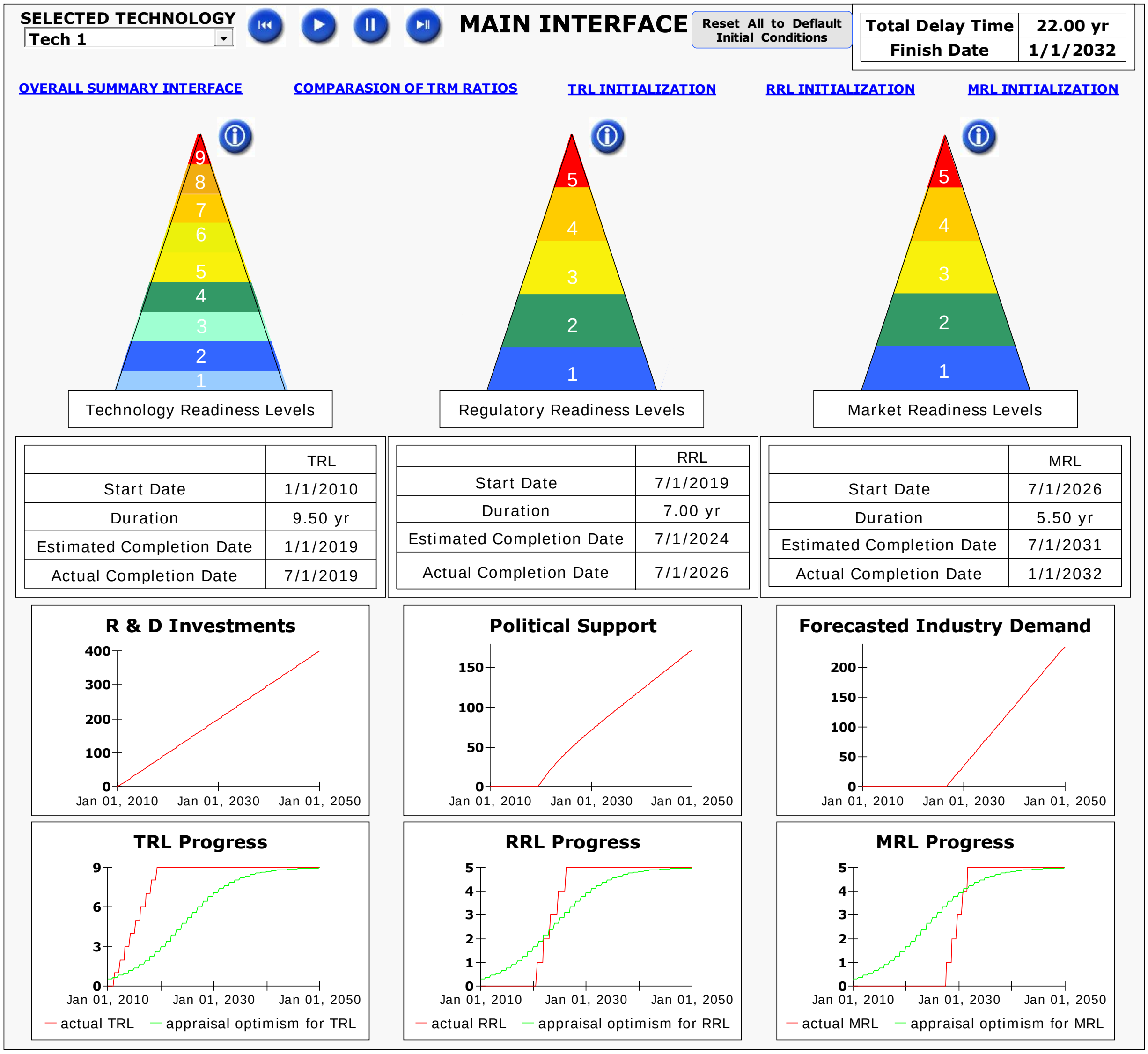
[3] Total Delay Time = 22 years; Assuming the technology’s research started in the year 2010, it would not be complete and ready for the larger market by 2032.

RRL. Similarly, “Tech 1” must complete the five stages of the RRL before moving on to the MRL. Logically, this matches a common pathway for technology development (but certainly not all technologies) where the technology is first invented, becomes operational, gains the regulatory support necessary to become an option to the marketplace, and then enters the marketplace where firms take some time to build factories and begin producing the technology.

There are currently 3 different technologies in TRMsim one can select to compare the time it takes for one technology to fully progress ‘from the mind to the market’. To the left of this pull down option box are the ‘play’ type of buttons to operate the model, and other model navigation panes that take the user to different model input options. These additional navigation panes include the ‘comparison of TRM ratios’ that illustrate thresholds to which the research can be held before ending funding support. That is, an investor may set criteria to judge whether sufficient progress in the TRL spectrum occurs and if not the investor may withhold all funding and stop the research. Next, the ‘TRL initialization’, ‘RRL Initialization’ and ‘MRL Initialization’ links takes the model user to the input options for the TRL, RRL and MRL components, respectively. The blue-colored icons with the ‘i’ in them explain the levels associated with tech of the three readiness levels (RLs). For example, the icon to the upper right-hand side of the TRL pyramid gives a longer explanation as to what levels 1 – 9 mean for the technology under investigation. Similarly, the icons next to the RRL and MRL pyramids explain what each of their respective five levels mean for the technology to progress through a regulatory process and market development process, respectively.



SELECTED TECHNOLOGY: Tech 1

Total Delay Time	22.00 yr
Finish Date	1/1/2032

	TRL
Start Date	1/1/2010
Duration	9.50 yr
Estimated Completion Date	1/1/2019
Actual Completion Date	7/1/2019

	RRL
Start Date	7/1/2019
Duration	7.00 yr
Estimated Completion Date	7/1/2024
Actual Completion Date	7/1/2026

	MRL
Start Date	7/1/2026
Duration	5.50 yr
Estimated Completion Date	7/1/2031
Actual Completion Date	1/1/2032

Figure 5. Main interface screen for the Technology, Regulatory and Market Readiness Level Simulation model (TRMsim).

5.2 Technology Readiness Level (TRL) Module

The transition through the nine levels of Technology Readiness Level (TRL) spectrum is a discrete process of stepping to the next level based on achieving the metric of R&D Spending requirements in millions of United States Dollars (USD) for each level.[4] The requirement for incremental R&D spending for each TRL is set initially by the user using an interactive column graph in the TRL Initialization page. The driving behavior of this progression is the

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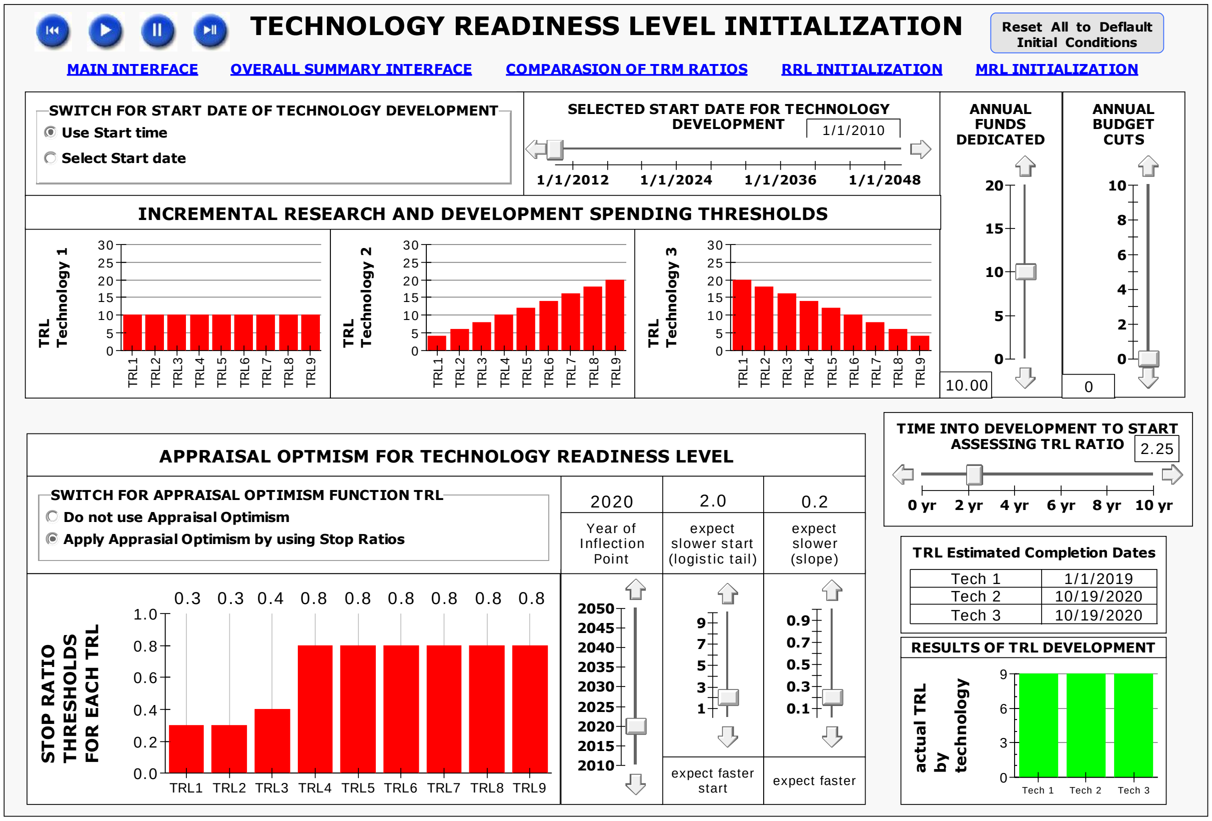
[4] The nine TRLs modeled in TRMsim include: (1) Basic Principles Observed, (2) Technology Concept Formulated, (3) Research and Development Initiated, (4) Integrated Key Elements Validated in Laboratory, (5) Relevant Environment Validated with Supporting Elements, (6) Prototype Tested in Relevant Environment, (7) Prototype Demonstrated in Operational Environment, (8) Actual Deliverable Qualified and (9) Operational Use.

accumulation of the Research and Development (R&D) spending based on annual funds dedicated, also this R&D investment collection can decrease through annual budget cuts. The TRMsim users can set the annual budget cuts at the start or later in the simulation. The process of advancing through TRLs can be automatically determined to stop based on progress through TRLs not meeting the expected (and user-determined) acceptable range in the progress differential (Stop Ratio Thresholds). That is, if the investor does not see sufficient progress being made in the technology's research, they may choose to completely stop funding it and thereby end the R&D process which the TRL framework represents. Additionally, the start date for the technology development can be delayed for all technologies, simultaneously.



SWITCH FOR START DATE OF TECHNOLOGY DEVELOPMENT
● Use Start time
○ Select Start date

SELECTED START DATE FOR TECHNOLOGY DEVELOPMENT 1/1/2010

ANNUAL FUNDS DEDICATED 10.00

ANNUAL BUDGET CUTS 0

TIME INTO DEVELOPMENT TO START ASSESSING TRL RATIO 2.25

SWITCH FOR APPRAISAL OPTIMISM FUNCTION TRL
○ Do not use Appraisal Optimism
● Apply Apprasial Optimism by using Stop Ratios

Year of Inflection Point 2020
expect slower start (logistic tail) 2.0
expect slower (slope) 0.2

TRL Estimated Completion Dates

Tech 1	1/1/2019
Tech 2	10/19/2020
Tech 3	10/19/2020

Figure 6. Technology Readiness Level Initialization Model Input Options to compare Technological Progress.

5.3 Regulatory Readiness Level (RRL) Module

The progress of achieving the five stages of Regulatory Readiness Levels (RRL) is a discrete process driven by reaching requirements for Political Support units (traction units as the driver) to represent the application of political support towards a technology.[5] The incremental requirement for Political Support at each RRL is set by the user in the RRL initialization page

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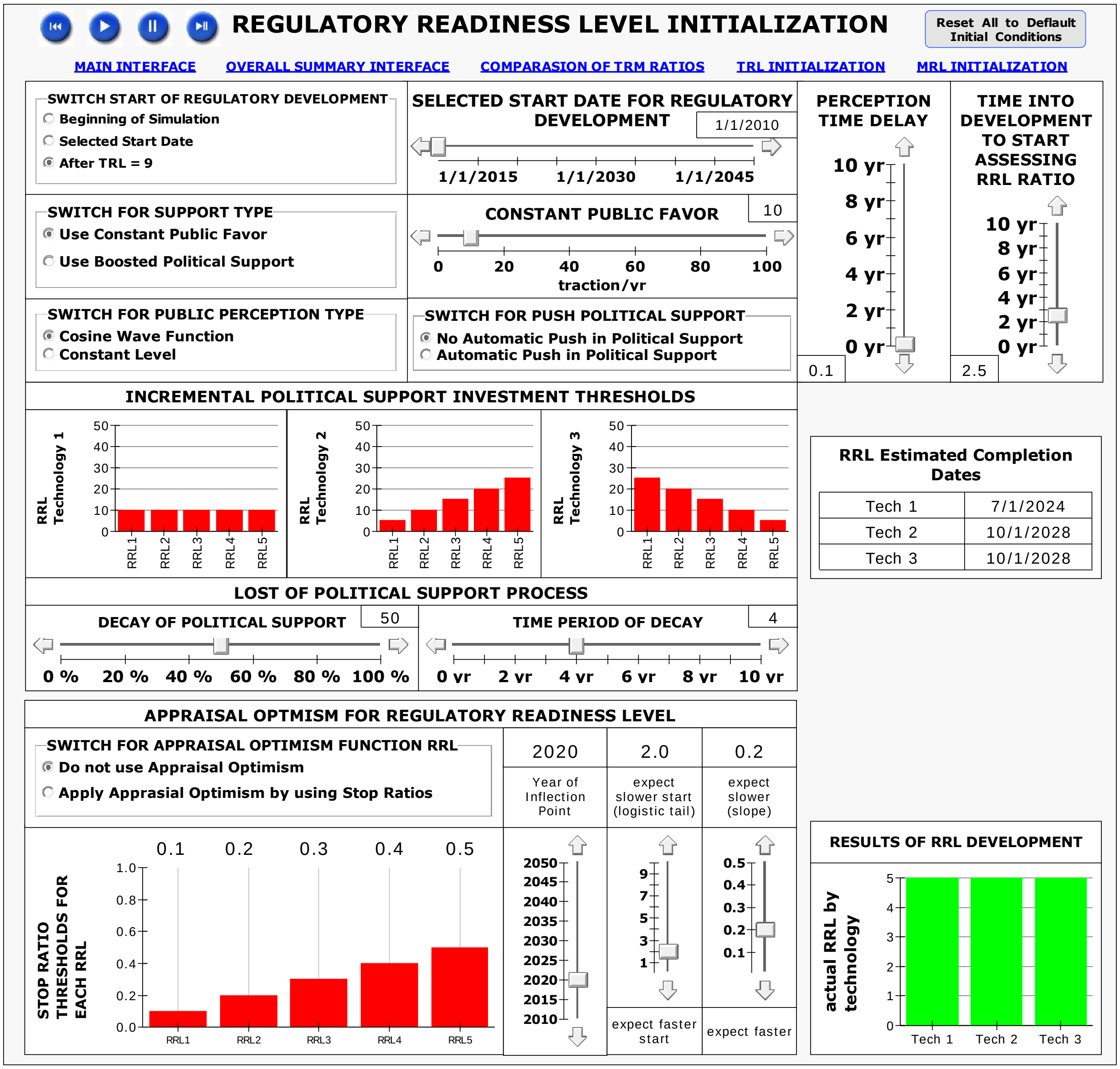
[5] The five levels of the RRL include: (1) Access to Regulatory Process, (2) Security of Political Capital, (3) Policy Effectiveness, (4) Do No Harm and (5) Political Acceptability.

using an interactive column graph. The driving force (traction units) in accumulating Political Support could be achieved by three independent mechanisms of:

- Constant input of public favor for Political Support,
- Cyclic process of Political Support obtained from General Public and Congress, and
- Automatic Push of Political Support to achieve level 3 of RRL (As a hypothetical assumption to test the Policy Effectiveness of an effort that is not just starting out, but did not finish yet either)

The accumulation of Political Support decreases through a concept of disinterest based on time delay and percentage of lost support. The development of the RRL can be stopped based on the actual progress not being within an acceptable range for expected progress for that time period. The user can determine the acceptable range of difference within the RRL Initialization settings. The start date of the RRL development can be set in three ways:

- At the start of the simulation,
- User-determined date, or
- The progress will begin after all Technology Readiness Levels are obtained for that technology.



SWITCH START OF REGULATORY DEVELOPMENT
○ Beginning of Simulation
○ Selected Start Date
● After TRL = 9

SELECTED START DATE FOR REGULATORY DEVELOPMENT: 1/1/2010

PERCEPTION TIME DELAY: 0.1

TIME INTO DEVELOPMENT TO START ASSESSING RRL RATIO: 2.5

SWITCH FOR SUPPORT TYPE
● Use Constant Public Favor
○ Use Boosted Political Support

CONSTANT PUBLIC FAVOR: 10

SWITCH FOR PUBLIC PERCEPTION TYPE
● Cosine Wave Function
○ Constant Level

SWITCH FOR PUSH POLITICAL SUPPORT
● No Automatic Push in Political Support
○ Automatic Push in Political Support

RRL Estimated Completion Dates

Tech 1	7/1/2024
Tech 2	10/1/2028
Tech 3	10/1/2028

DECAY OF POLITICAL SUPPORT: 50

TIME PERIOD OF DECAY: 4

SWITCH FOR APPRAISAL OPTIMISM FUNCTION RRL
● Do not use Appraisal Optimism
○ Apply Apprasial Optimism by using Stop Ratios

Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)
2020	2.0	0.2

Figure 7. Regulatory Readiness Level Initialization Model Input Options to compare Regulatory Progress.

5.4 Market Readiness Level (MRL) Module

The progress of the five Market Readiness Level stages is a discrete process driven by obtaining the requirements of Potential Industry Demand in units of investment units.[6] The incremental requirement for Potential Industry Demand at each MRL is set by the user in the MRL initialization page using an interactive column graph. The driving force in the accumulation of Industry Demand develops from both constant demand increase, and demand pull mechanism with a policy target that results in an internally-determined constant parameter.

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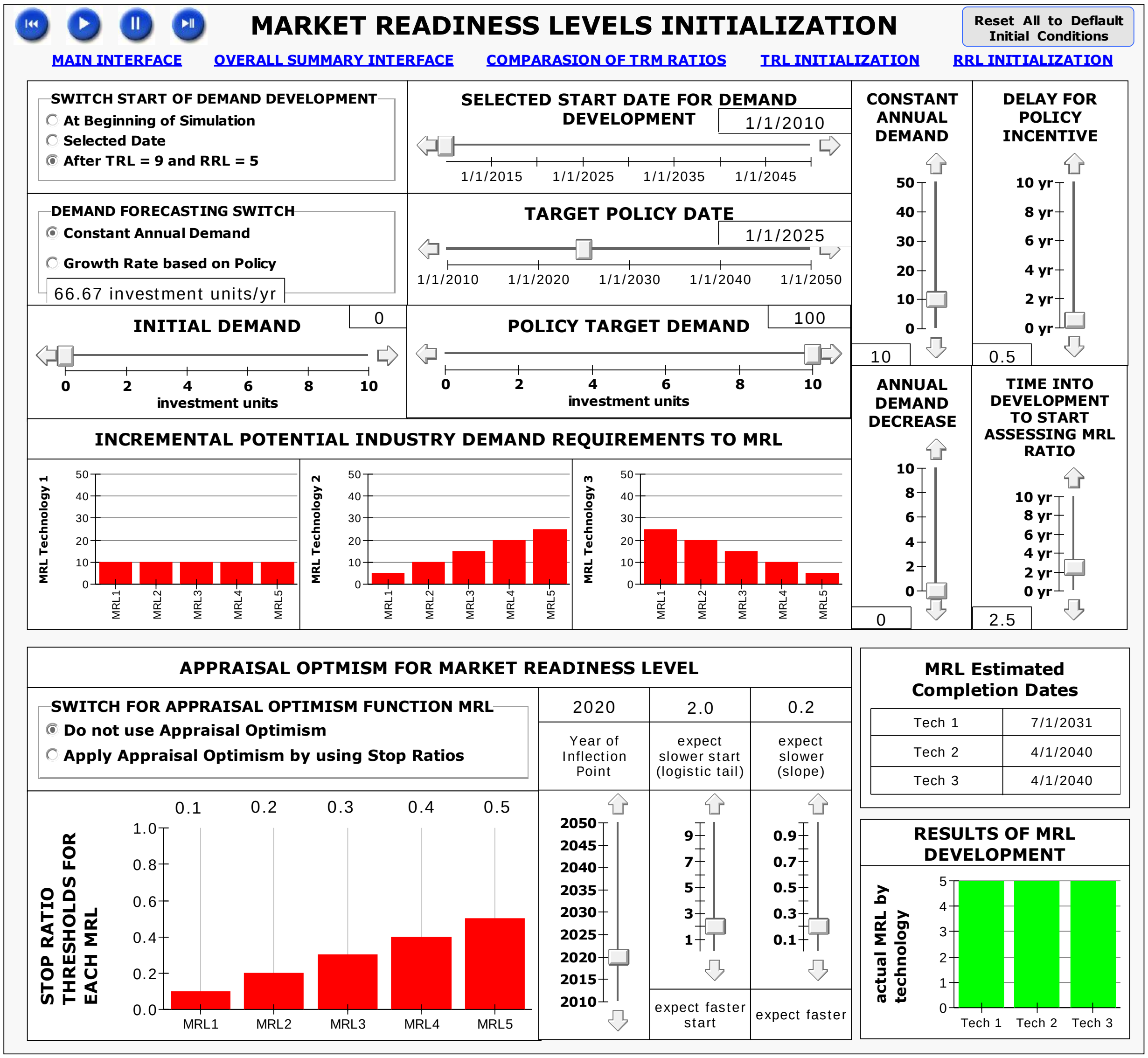
[6] The five levels of the MRL include: (1) Access to Market Base, (2) Security of Financial Capital, (3) Market Cost Competitive, (4) Profitable and (5) Consumer Utility.

In addition, both of those processes can be increased using incentives that will have a delayed effect. The Potential Industry Demand can be decreased annually using a constant parameter value. The development of the MRL can be stopped based on the actual progress not being within an acceptable range of expected progress for that time period. The user can determine the acceptable range of difference within the MRL's Initialization. The start date of the demand development can be set using three methods:

- At the beginning of the simulation,
- At the user selected start date, or
- After the TRL and RRL reached their maximum levels.



MARKET READINESS LEVELS INITIALIZATION

SWITCH START OF DEMAND DEVELOPMENT
○ At Beginning of Simulation
○ Selected Date
● After TRL = 9 and RRL = 5

SELECTED START DATE FOR DEMAND DEVELOPMENT: 1/1/2010

DEMAND FORECASTING SWITCH
● Constant Annual Demand
○ Growth Rate based on Policy
66.67 investment units/yr

TARGET POLICY DATE: 1/1/2025

INITIAL DEMAND: 0

POLICY TARGET DEMAND: 100

CONSTANT ANNUAL DEMAND: 10

DELAY FOR POLICY INCENTIVE: 0.5

ANNUAL DEMAND DECREASE: 0

TIME INTO DEVELOPMENT TO START ASSESSING MRL RATIO: 2.5

APPRAISAL OPTMISM FOR MARKET READINESS LEVEL

SWITCH FOR APPRAISAL OPTIMISM FUNCTION MRL
● Do not use Appraisal Optimism
○ Apply Appraisal Optimism by using Stop Ratios

2020	2.0	0.2
Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)

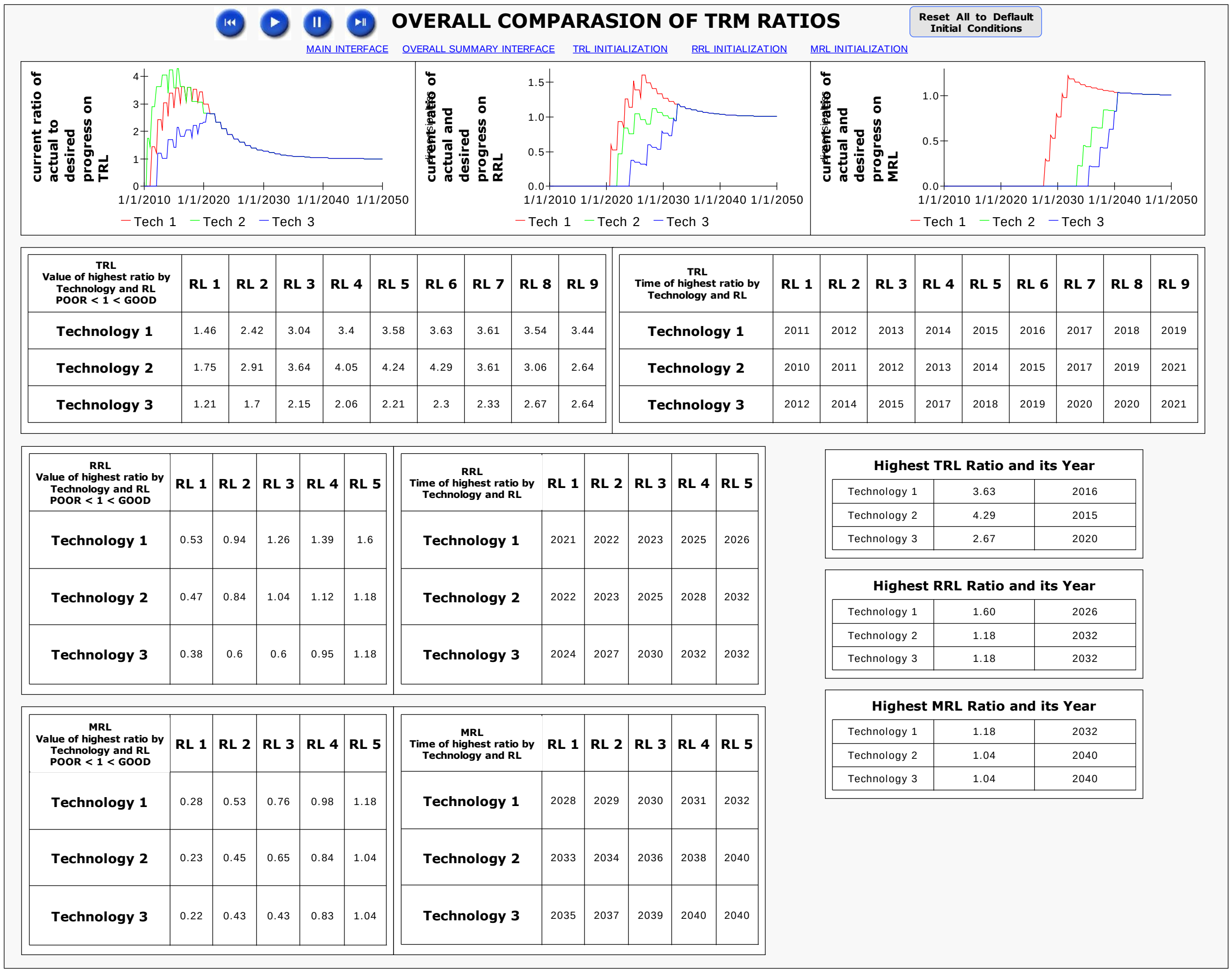
MRL Estimated Completion Dates

Tech 1	7/1/2031
Tech 2	4/1/2040
Tech 3	4/1/2040

Figure 8. Market Readiness Level Model Input Options to compare Market Development and Progress.

5.5 Technology, Regulatory and Market Readiness Ratios for Appraisal Optimism.

Appraisal optimism within TRMsim is the concept of an evaluator's expectation on progress (Jeffrey et al., 2013). This expectation develops from the evaluator's general knowledge of trends in developing the three readiness types. The progress of the appraisal optimism for each readiness type within TRMsim builds from a logistic curve ('S-shaped' curve) for which the user can set these parameters as well. The option to apply the appraisal optimism concept is the decision on whether the technology should stop based on user-determined progress differentials (Stop Ratio Thresholds). The ratio of the actual to the expected progress illustrates a progress differential (trigger ratios) for a specific technology. If the progress differential reaches a predetermined size, then that technology will stop accumulating the driving force for that RL type thereby terminating its development. The decision to stop development will directly affect the driving forces of funding, political support, and investments for TRL, RRL, and MRL, respectively.



TRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	1.46	2.42	3.04	3.4	3.58	3.63	3.61	3.54	3.44
Technology 2	1.75	2.91	3.64	4.05	4.24	4.29	3.61	3.06	2.64
Technology 3	1.21	1.7	2.15	2.06	2.21	2.3	2.33	2.67	2.64

TRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	2011	2012	2013	2014	2015	2016	2017	2018	2019
Technology 2	2010	2011	2012	2013	2014	2015	2017	2019	2021
Technology 3	2012	2014	2015	2017	2018	2019	2020	2020	2021

RRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0.53	0.94	1.26	1.39	1.6
Technology 2	0.47	0.84	1.04	1.12	1.18
Technology 3	0.38	0.6	0.6	0.95	1.18

RRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2021	2022	2023	2025	2026
Technology 2	2022	2023	2025	2028	2032
Technology 3	2024	2027	2030	2032	2032

MRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0.28	0.53	0.76	0.98	1.18
Technology 2	0.23	0.45	0.65	0.84	1.04
Technology 3	0.22	0.43	0.43	0.83	1.04

MRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2028	2029	2030	2031	2032
Technology 2	2033	2034	2036	2038	2040
Technology 3	2035	2037	2039	2040	2040

Highest TRL Ratio and its Year

Technology 1	3.63	2016
Technology 2	4.29	2015
Technology 3	2.67	2020

Highest RRL Ratio and its Year

Technology 1	1.60	2026
Technology 2	1.18	2032
Technology 3	1.18	2032

Highest MRL Ratio and its Year

Technology 1	1.18	2032
Technology 2	1.04	2040
Technology 3	1.04	2040

Figure 9. Technology, Regulatory and Market Investment Trigger Ratios.

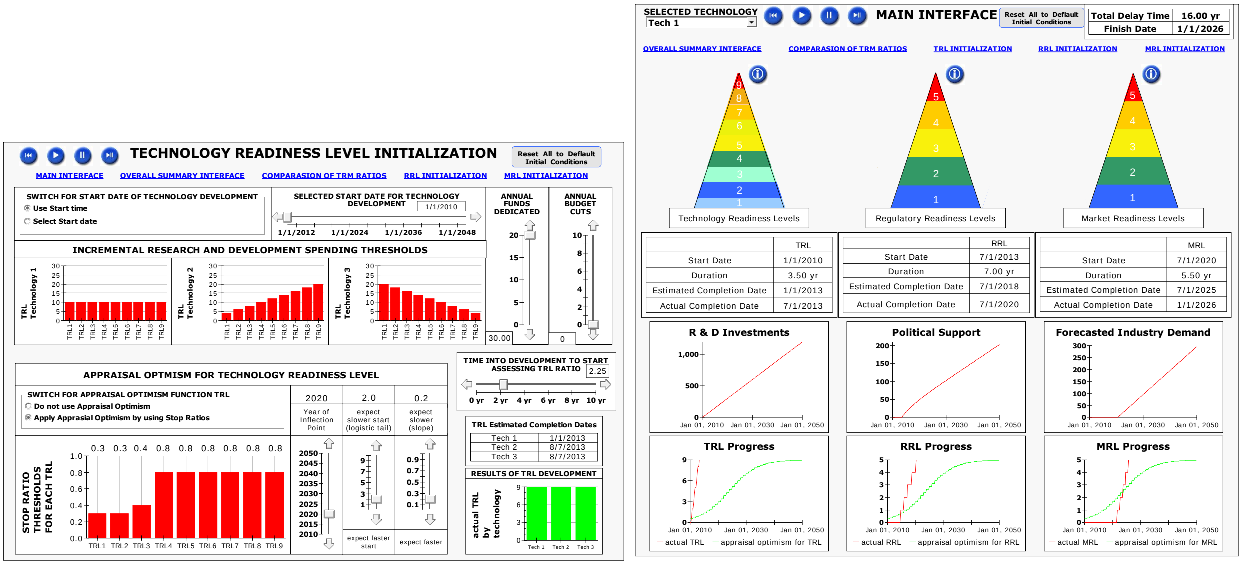
6. DISCUSSION

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 political term limitations and ambitions, 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 TRMsim model 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 TRMsim model illustrates just 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.

6.1 Example Policy Goal Timing

The set of user options within TRMsim can help analysts focus on steps required to speed up technology research, development and deployment. For example, if a policy exists with the goal to field new technologies with lower emissions by 2030, increasing the funds allocated to research may also increase the likelihood of that technology moving from the laboratory to the marketplace sooner. Figure 10 illustrates a situation if one were to triple the expenditures in a hypothetical technology case.



SWITCH FOR START DATE OF TECHNOLOGY DEVELOPMENT
● Use Start time
○ Select Start date

SELECTED START DATE FOR TECHNOLOGY DEVELOPMENT: 1/1/2010

ANNUAL FUNDS DEDICATED: 30.00

ANNUAL BUDGET CUTS: 0

TIME INTO DEVELOPMENT TO START ASSESSING TRL RATIO: 2.25

SWITCH FOR APPRAISAL OPTIMISM FUNCTION TRL
○ Do not use Appraisal Optimism
● Apply Apprasial Optimism by using Stop Ratios

2020	2.0	0.2
Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)

TRL Estimated Completion Dates

Tech 1	1/1/2013
Tech 2	8/7/2013
Tech 3	8/7/2013

SELECTED TECHNOLOGY: Tech 1

Total Delay Time	16.00 yr
Finish Date	1/1/2026

	TRL
Start Date	1/1/2010
Duration	3.50 yr
Estimated Completion Date	1/1/2013
Actual Completion Date	7/1/2013

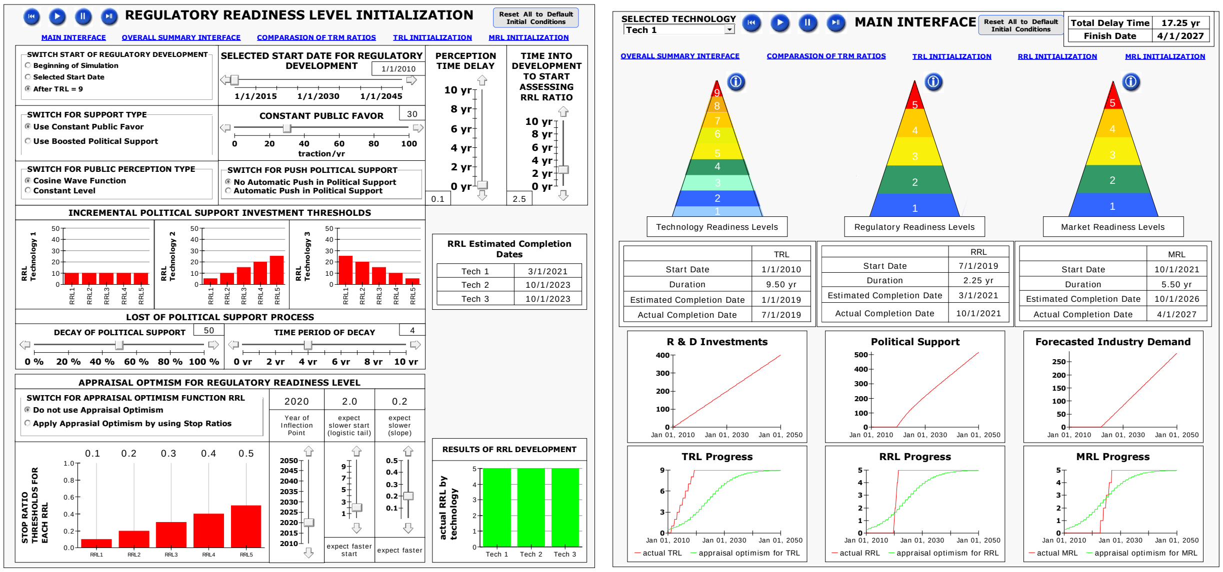
	RRL
Start Date	7/1/2013
Duration	7.00 yr
Estimated Completion Date	7/1/2018
Actual Completion Date	7/1/2020

	MRL
Start Date	7/1/2020
Duration	5.50 yr
Estimated Completion Date	7/1/2025
Actual Completion Date	1/1/2026

Figure 10. Driving the TRL Faster by Tripling the R&D Funding (parameter inputs (left), main interface results (right)).

Comparing Figures 5 and 10, by increasing the funding to three times the base case the results indicate the TRL will drive from 1 to 9 in only 3.5 years rather than 9.5. This decreases the entire TRL, RRL and MRL timeline down from 22 year to 16 years. This is an example of a stylized situation where policy could, through increased funding, succeed in speeding up a technology's progression from the laboratory to deployment in the marketplace.

Similarly, one can drive the RRL faster than in the base case by increasing the political traction per year (e.g., more influential and effective policy actions) that assist a technology by clearing regulatory hurdles and allowing the technology to enter the market sooner. Figure 11 illustrates an accelerated political support by increasing the 'constant public favor' from 10 traction units per year to 30.



REGULATORY READINESS LEVEL INITIALIZATION

SWITCH START OF REGULATORY DEVELOPMENT
○ Beginning of Simulation
○ Selected Start Date
● After TRL = 9

SELECTED START DATE FOR REGULATORY DEVELOPMENT: 1/1/2010

PERCEPTION TIME DELAY: 0.1

TIME INTO DEVELOPMENT TO START ASSESSING RRL RATIO: 2.5

SWITCH FOR SUPPORT TYPE
● Use Constant Public Favor
○ Use Boosted Political Support

CONSTANT PUBLIC FAVOR: 30 traction/yr

SWITCH FOR PUBLIC PERCEPTION TYPE
● Cosine Wave Function
○ Constant Level

SWITCH FOR PUSH POLITICAL SUPPORT
● No Automatic Push in Political Support
○ Automatic Push in Political Support

RRL Estimated Completion Dates

Tech 1	3/1/2021
Tech 2	10/1/2023
Tech 3	10/1/2023

LOST OF POLITICAL SUPPORT PROCESS

DECAY OF POLITICAL SUPPORT: 50

TIME PERIOD OF DECAY: 4

APPRAISAL OPTMISM FOR REGULATORY READINESS LEVEL

SWITCH FOR APPRAISAL OPTIMISM FUNCTION RRL
● Do not use Appraisal Optimism
○ Apply Apprasial Optimism by using Stop Ratios

2020	2.0	0.2
Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)

RESULTS OF RRL DEVELOPMENT

MAIN INTERFACE

SELECTED TECHNOLOGY: Tech 1

Total Delay Time	17.25 yr
Finish Date	4/1/2027

	TRL
Start Date	1/1/2010
Duration	9.50 yr
Estimated Completion Date	1/1/2019
Actual Completion Date	7/1/2019

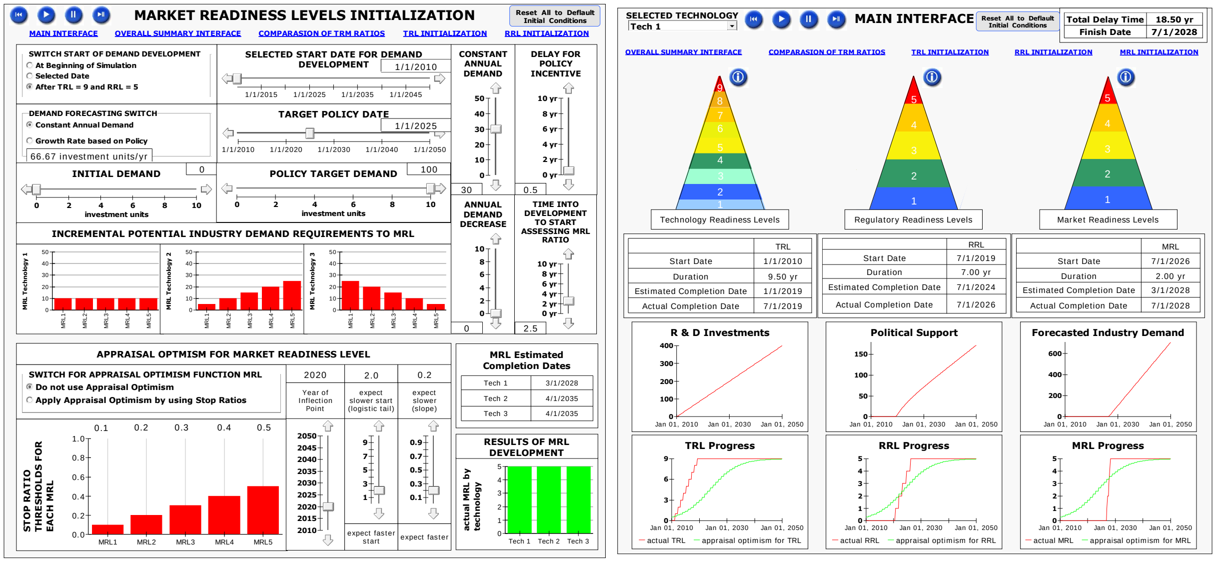
	RRL
Start Date	7/1/2019
Duration	2.25 yr
Estimated Completion Date	3/1/2021
Actual Completion Date	10/1/2021

	MRL
Start Date	10/1/2021
Duration	5.50 yr
Estimated Completion Date	10/1/2026
Actual Completion Date	4/1/2027

Figure 11. Driving the RRL Faster by Tripling the Public Support for a given Technology (parameter inputs (left), main interface results (right)).

Comparing Figures 5 and 11, by increasing the public favor to three times the base case the results indicate the RRL will drive from 1 to 5 in only 2.25 years rather than 7. This decreases the entire TRL, RRL and MRL timeline down from 22 year to 17.25 years. This is an example of a stylized situation where securing stronger political support immediately after a technology completes the TRL development through increased political support could help speed up a technology's progression to market.

Next, by increasing (or noting) the potential increases in annual market demand for a new or innovative product, one can also increase the speed at which the technology progresses through MRL. By tripling the quantity demanded per year, this reduces the time it may take over the base case to progress through the MRL from 5.5 down to 2 years. The overall system, therefore, would be completed in only 18.5 years rather than 22.



SWITCH START OF DEMAND DEVELOPMENT
○ At Beginning of Simulation
○ Selected Date
● After TRL = 9 and RRL = 5

SELECTED START DATE FOR DEMAND DEVELOPMENT: 1/1/2010

CONSTANT ANNUAL DEMAND: 30

DELAY FOR POLICY INCENTIVE: 0.5

DEMAND FORECASTING SWITCH
● Constant Annual Demand
○ Growth Rate based on Policy
66.67 investment units/yr

TARGET POLICY DATE: 1/1/2025

INITIAL DEMAND: 0

POLICY TARGET DEMAND: 100

ANNUAL DEMAND DECREASE: 0

TIME INTO DEVELOPMENT TO START ASSESSING MRL RATIO: 2.5

SWITCH FOR APPRAISAL OPTIMISM FUNCTION MRL
● Do not use Appraisal Optimism
○ Apply Appraisal Optimism by using Stop Ratios

2020	2.0	0.2
Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)

MRL Estimated Completion Dates

Tech 1	3/1/2028
Tech 2	4/1/2035
Tech 3	4/1/2035

SELECTED TECHNOLOGY: Tech 1

Total Delay Time	18.50 yr
Finish Date	7/1/2028

	TRL
Start Date	1/1/2010
Duration	9.50 yr
Estimated Completion Date	1/1/2019
Actual Completion Date	7/1/2019

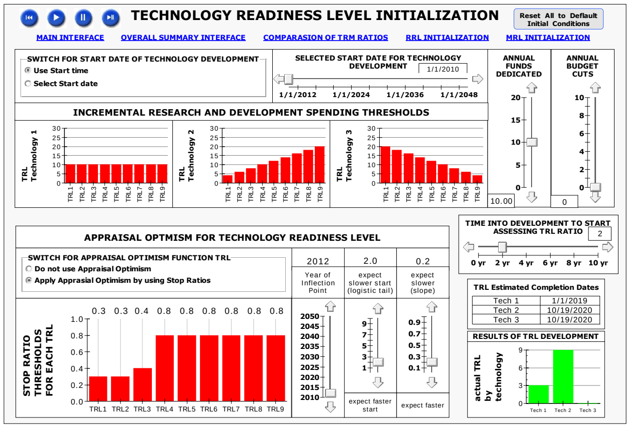
	RRL
Start Date	7/1/2019
Duration	7.00 yr
Estimated Completion Date	7/1/2024
Actual Completion Date	7/1/2026

	MRL
Start Date	7/1/2026
Duration	2.00 yr
Estimated Completion Date	3/1/2028
Actual Completion Date	7/1/2028

Figure 12. Driving the MRL Faster by Tripling the Quantity Demanded per year for a given Technology (parameter inputs (left), main interface results (right)).

In addition to adjusting the input parameters to the TRL, RRL and MRL, TRMsim allows for investment decision cut off points to be determined. This allows for scenarios that give technology (in the TRL) the chance to prove itself by meeting expectations for an investor's RD&D funds. If the invention or innovation is not moving at a pace in line with the investor's desires, the project stops after failing to reach a pre-determined threshold.

Figure 13 illustrates a more restrictive set of conditions under which the TRL is expected to perform. This simulates a more demanding investor that begins evaluating the progress of the research after the first two years. The investor also expects progress to be more expeditious in the initial years of the project as shown by using the Appraisal Optimism inflection point at a more aggressive level of 2 years after research begins rather than 10. The project therefore does not succeed under these more demanding conditions, and ends once the R&D of the TRL is in the third tier representing, 'Research and Development Initiated' just beyond the basic principles and technology concept stages 1 and 2, respectively.



SWITCH FOR START DATE OF TECHNOLOGY DEVELOPMENT
● Use Start time
○ Select Start date

SELECTED START DATE FOR TECHNOLOGY DEVELOPMENT: 1/1/2010

ANNUAL FUNDS DEDICATED: 10.00

ANNUAL BUDGET CUTS: 0

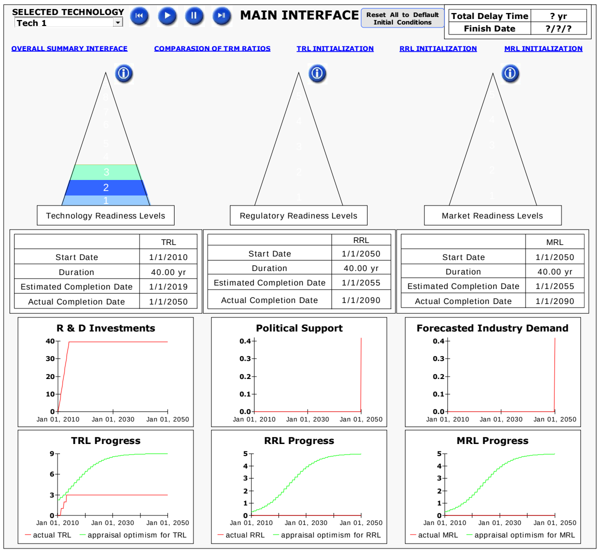
SWITCH FOR APPRAISAL OPTIMISM FUNCTION TRL
○ Do not use Appraisal Optimism
● Apply Apprasial Optimism by using Stop Ratios

2012	2.0	0.2
Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)

TIME INTO DEVELOPMENT TO START ASSESSING TRL RATIO: 2

TRL Estimated Completion Dates

Tech 1	1/1/2019
Tech 2	10/19/2020
Tech 3	10/19/2020



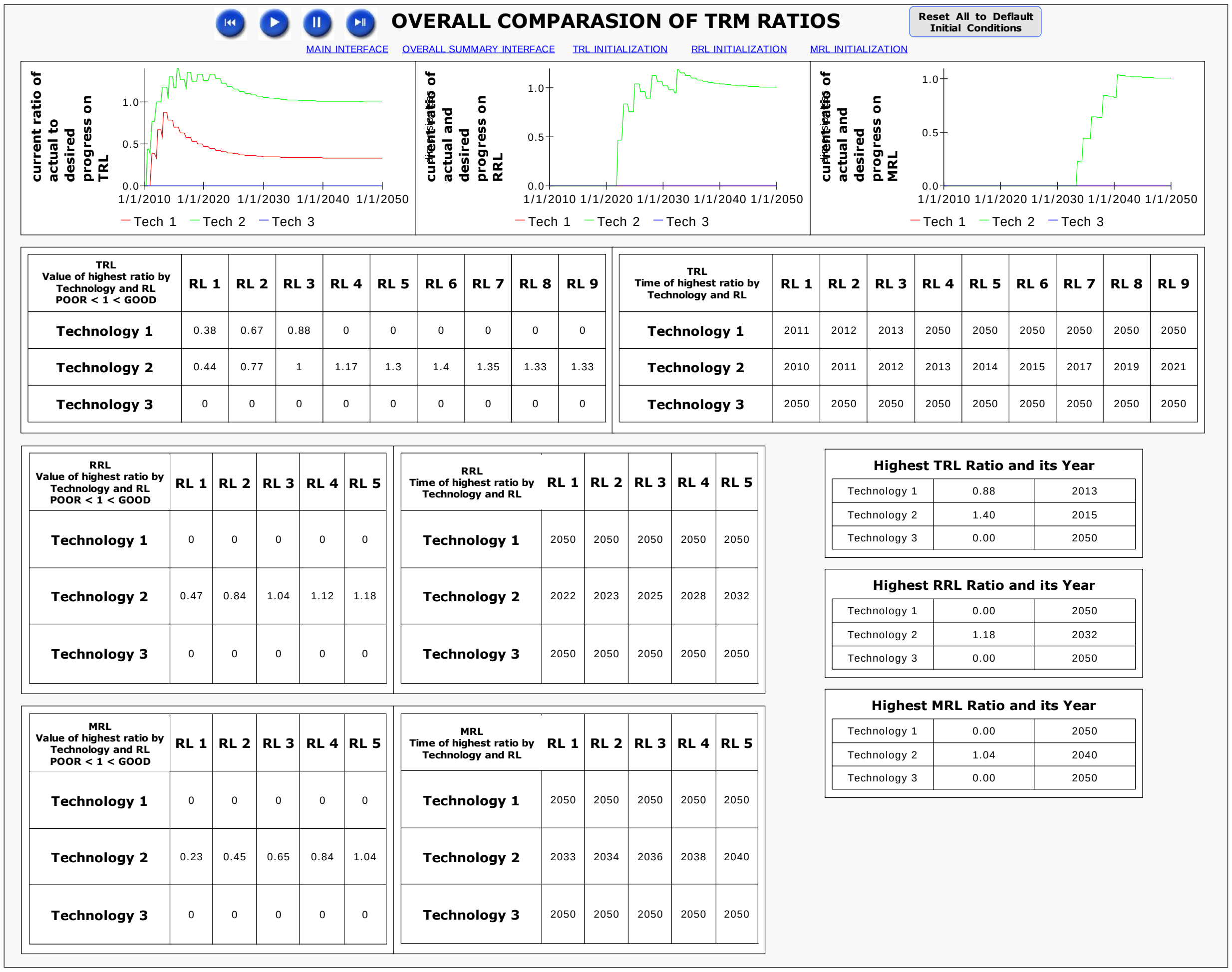
SELECTED TECHNOLOGY: Tech 1

Total Delay Time	? yr
Finish Date	?/?/?

	TRL
Start Date	1/1/2010
Duration	40.00 yr
Estimated Completion Date	1/1/2019
Actual Completion Date	1/1/2050

	RRL
Start Date	1/1/2050
Duration	40.00 yr
Estimated Completion Date	1/1/2055
Actual Completion Date	1/1/2090

	MRL
Start Date	1/1/2050
Duration	40.00 yr
Estimated Completion Date	1/1/2055
Actual Completion Date	1/1/2090



TRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	0.38	0.67	0.88	0	0	0	0	0	0
Technology 2	0.44	0.77	1	1.17	1.3	1.4	1.35	1.33	1.33
Technology 3	0	0	0	0	0	0	0	0	0

TRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	2011	2012	2013	2050	2050	2050	2050	2050	2050
Technology 2	2010	2011	2012	2013	2014	2015	2017	2019	2021
Technology 3	2050	2050	2050	2050	2050	2050	2050	2050	2050

RRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0	0	0	0	0
Technology 2	0.47	0.84	1.04	1.12	1.18
Technology 3	0	0	0	0	0

RRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2050	2050	2050	2050	2050
Technology 2	2022	2023	2025	2028	2032
Technology 3	2050	2050	2050	2050	2050

MRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0	0	0	0	0
Technology 2	0.23	0.45	0.65	0.84	1.04
Technology 3	0	0	0	0	0

MRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2050	2050	2050	2050	2050
Technology 2	2033	2034	2036	2038	2040
Technology 3	2050	2050	2050	2050	2050

Highest TRL Ratio and its Year

Technology 1	0.88	2013
Technology 2	1.40	2015
Technology 3	0.00	2050

Highest RRL Ratio and its Year

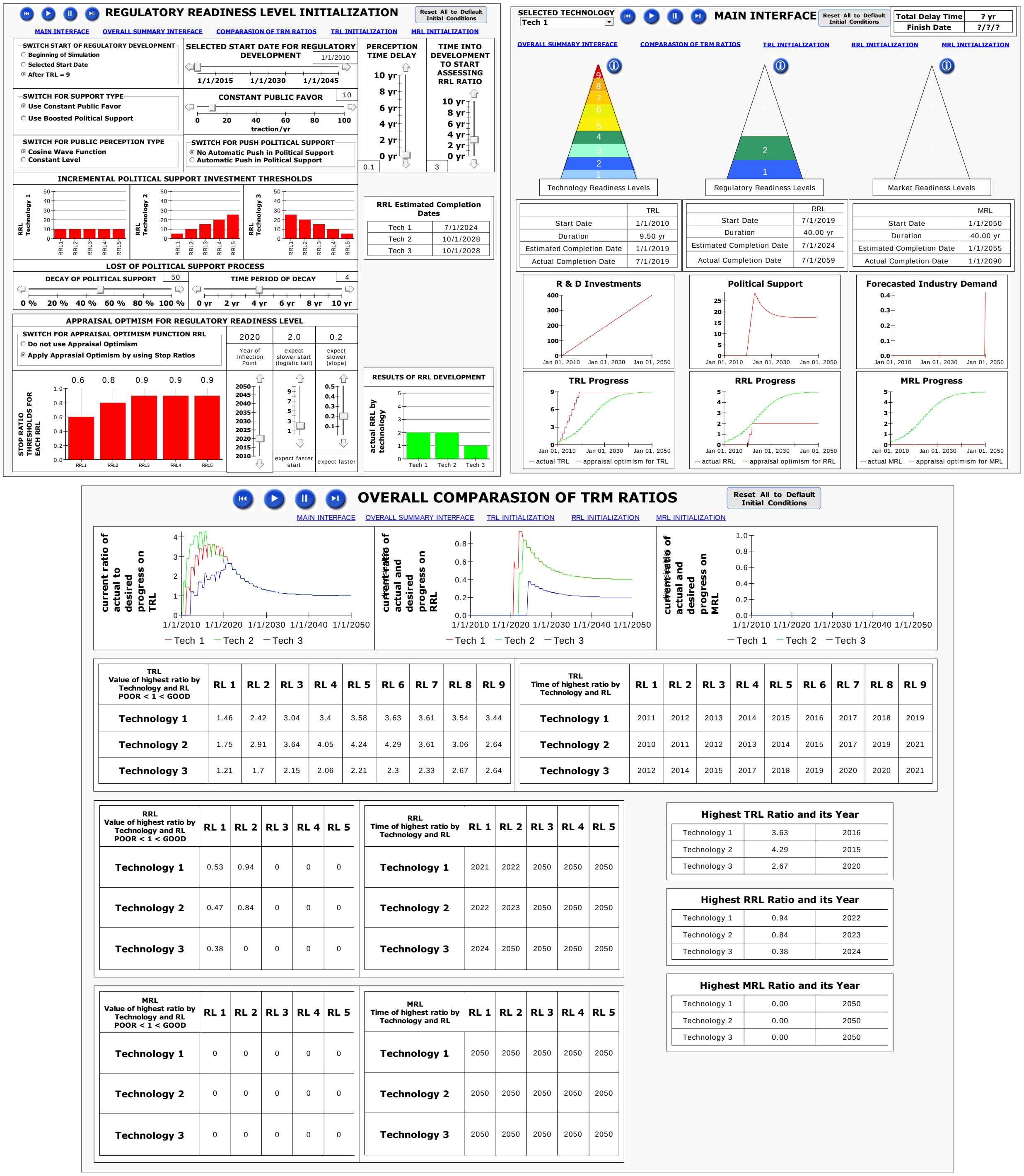
Technology 1	0.00	2050
Technology 2	1.18	2032
Technology 3	0.00	2050

Highest MRL Ratio and its Year

Technology 1	0.00	2050
Technology 2	1.04	2040
Technology 3	0.00	2050

Figure 13. Increasing the Investor's demands of the technology for higher performing TRL stages (parameter inputs (left), main interface results (right), ratios interface (bottom)).

Figure 14 illustrates the RRL ratio or ‘appraisal optimism’ options to determine if sufficient political support exists for a technology after it completes its R&D stages within the TRL spectrum.



REGULATORY READINESS LEVEL INITIALIZATION

SWITCH START OF REGULATORY DEVELOPMENT
○ Beginning of Simulation
○ Selected Start Date
● After TRL = 9

SELECTED START DATE FOR REGULATORY DEVELOPMENT: 1/1/2010

SWITCH FOR SUPPORT TYPE
● Use Constant Public Favor
○ Use Boosted Political Support

CONSTANT PUBLIC FAVOR: 10 (traction/yr)

SWITCH FOR PUBLIC PERCEPTION TYPE
● Cosine Wave Function
○ Constant Level

SWITCH FOR PUSH POLITICAL SUPPORT
● No Automatic Push in Political Support
○ Automatic Push in Political Support

PERCEPTION TIME DELAY: 0.1

TIME INTO DEVELOPMENT TO START ASSESSING RRL RATIO: 3

INCREMENTAL POLITICAL SUPPORT INVESTMENT THRESHOLDS

RRL Estimated Completion Dates

Tech 1	7/1/2024
Tech 2	10/1/2028
Tech 3	10/1/2028

LOST OF POLITICAL SUPPORT PROCESS

DECAY OF POLITICAL SUPPORT: 50

TIME PERIOD OF DECAY: 4

APPRAISAL OPTMISM FOR REGULATORY READINESS LEVEL

SWITCH FOR APPRAISAL OPTIMISM FUNCTION RRL
○ Do not use Appraisal Optimism
● Apply Apprasial Optimism by using Stop Ratios

Year of Inflection Point	expect slower start (logistic tail)	expect slower (slope)
2020	2.0	0.2

SELECTED TECHNOLOGY: Tech 1

MAIN INTERFACE

Total Delay Time	? yr
Finish Date	?/?/?

	TRL
Start Date	1/1/2010
Duration	9.50 yr
Estimated Completion Date	1/1/2019
Actual Completion Date	7/1/2019

	RRL
Start Date	7/1/2019
Duration	40.00 yr
Estimated Completion Date	7/1/2024
Actual Completion Date	7/1/2059

	MRL
Start Date	1/1/2050
Duration	40.00 yr
Estimated Completion Date	1/1/2055
Actual Completion Date	1/1/2090

OVERALL COMPARASION OF TRM RATIOS

TRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	1.46	2.42	3.04	3.4	3.58	3.63	3.61	3.54	3.44
Technology 2	1.75	2.91	3.64	4.05	4.24	4.29	3.61	3.06	2.64
Technology 3	1.21	1.7	2.15	2.06	2.21	2.3	2.33	2.67	2.64

TRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5	RL 6	RL 7	RL 8	RL 9
Technology 1	2011	2012	2013	2014	2015	2016	2017	2018	2019
Technology 2	2010	2011	2012	2013	2014	2015	2017	2019	2021
Technology 3	2012	2014	2015	2017	2018	2019	2020	2020	2021

RRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0.53	0.94	0	0	0
Technology 2	0.47	0.84	0	0	0
Technology 3	0.38	0	0	0	0

RRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2021	2022	2050	2050	2050
Technology 2	2022	2023	2050	2050	2050
Technology 3	2024	2050	2050	2050	2050

MRL Value of highest ratio by Technology and RL POOR < 1 < GOOD	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	0	0	0	0	0
Technology 2	0	0	0	0	0
Technology 3	0	0	0	0	0

MRL Time of highest ratio by Technology and RL	RL 1	RL 2	RL 3	RL 4	RL 5
Technology 1	2050	2050	2050	2050	2050
Technology 2	2050	2050	2050	2050	2050
Technology 3	2050	2050	2050	2050	2050

Highest TRL Ratio and its Year

Technology 1	3.63	2016
Technology 2	4.29	2015
Technology 3	2.67	2020

Highest RRL Ratio and its Year

Technology 1	0.94	2022
Technology 2	0.84	2023
Technology 3	0.38	2024

Highest MRL Ratio and its Year

Technology 1	0.00	2050
Technology 2	0.00	2050
Technology 3	0.00	2050

Figure 14. Employing the TRM Ratios to test the ‘Appraisal Optimism’ of Expected to Actual Political Support Threshold (parameter inputs (left), main interface results (right), ratios interface (bottom)).

7. SUMMARY AND CONCLUSIONS

The very appealing aspect of this TRL, RRL and MRL framework and subsequent TRMsim tool is its wide applicability to not only fossil fuel energy systems as they relate to a transitioning energy portfolio in the electricity sector, but to all types of energy systems and technologies in various sectors. The research community that develops energy-economic-engineering types of models could benefit greatly from a tool such as TRMsim. The key benefits would be 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 a given target date). Studies that compare the results of energy, climate and engineering technology deployment models throughout the research community could benefit from the time delay lessons borne out of the TRMsim framework.

Using TRMsim to illustrate a policy influence to help move a technology more quickly from the research space to market can take many forms. Tripling the size or influence of the key driver to the technology, regulatory and market readiness level, for example, may reduce the time to complete each stage by 63%, 68% and 64%, respectively.[7] These working results illustrate that under the current parameter assumptions for this hypothetical example that investing three times the resources or influence in the regulatory readiness levels may help expedite the technology's progression through the regulatory processes faster than would a similar investment in the technology's readiness or market readiness development. These results, however, are hypothetical and very case-specific. Applying the model more widely likely requires additional real world information to adjust the model's input parameters to help model the time it takes to move the technology from the research stages to full market adoption. With this information comes an opportunity to assess the notion that the 'timing is everything' when looking to meet policy goals through technology-based solutions.

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[7] TRL drives from 1 to 9 in only 3.5 years rather than 9.5; RRL drives from 1 to 5 in only 2.25 years rather than 7; MRL drives from 1 to 5 in only 2 years rather than 5.5.

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APPENDIX A.

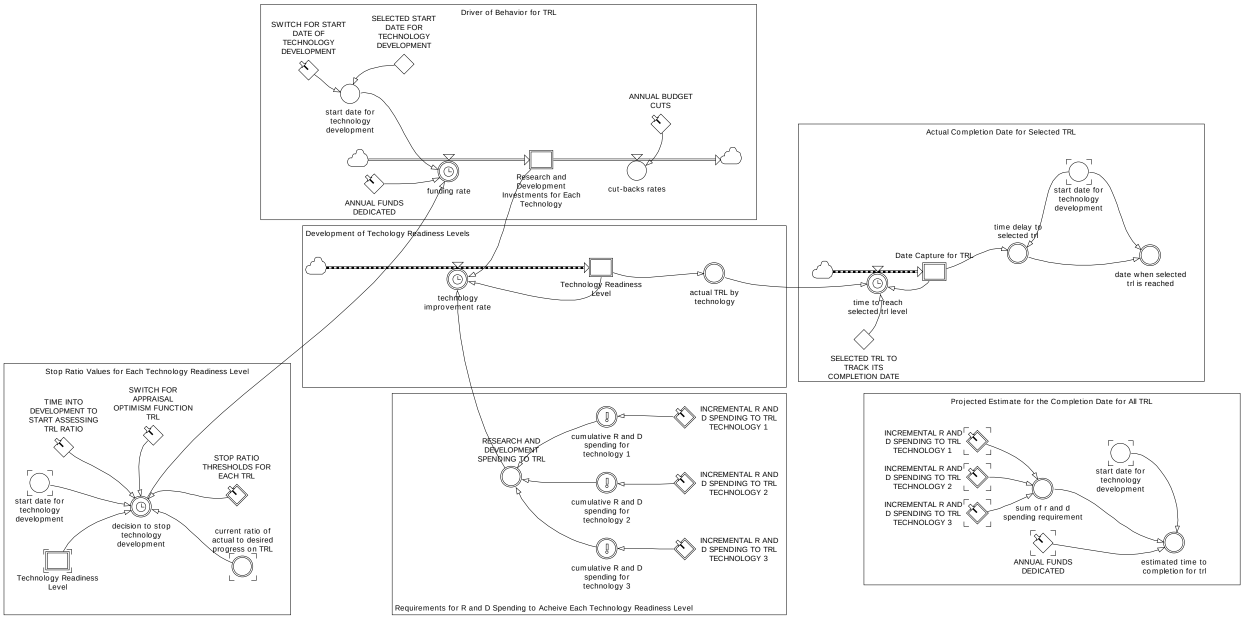

Figure A1a. Overall View of the Technology Readiness Level (TRL) sub-module.

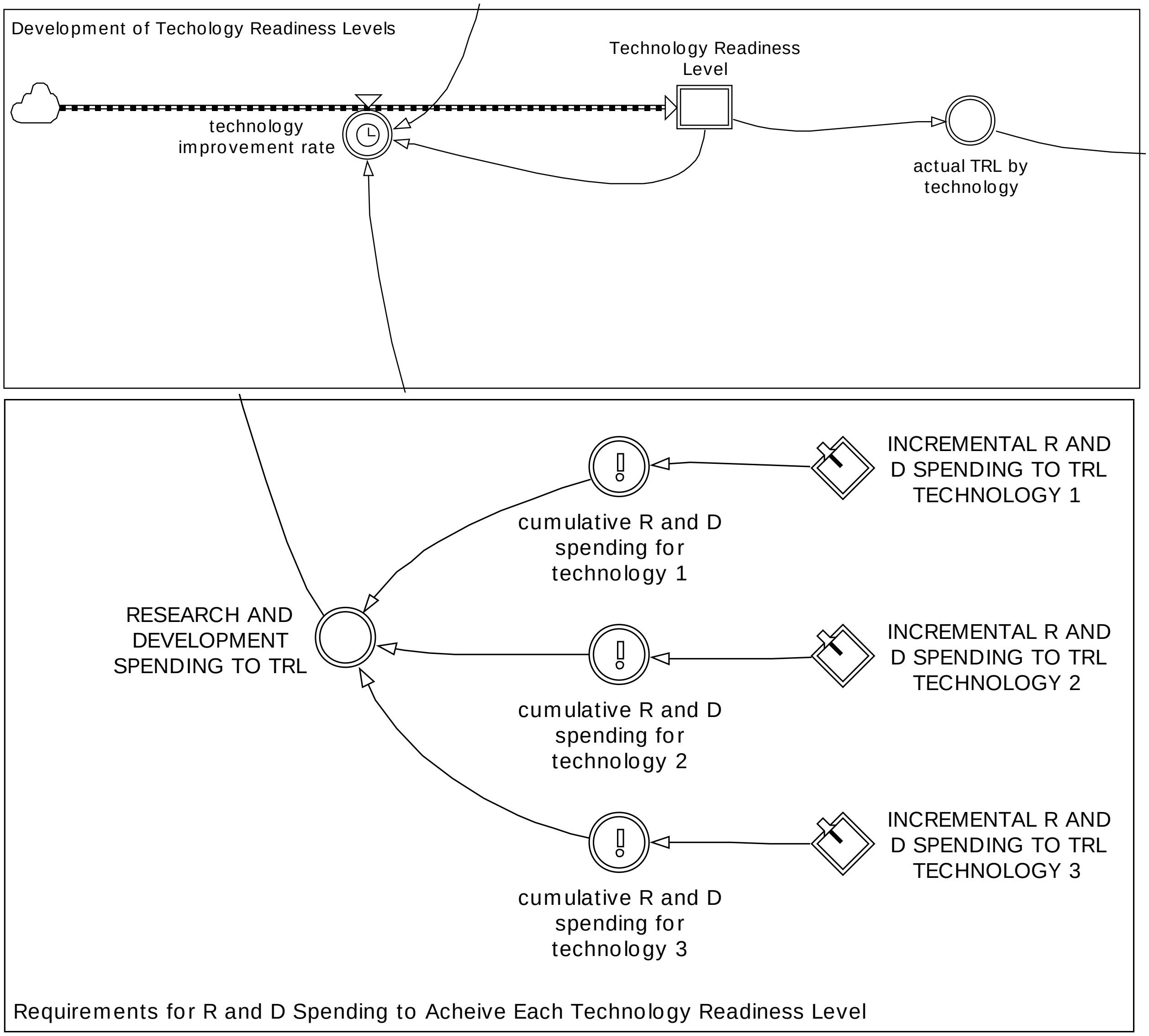

Figure A1b. The Core Components Detail for the Technology Readiness Level (TRL) sub-module.

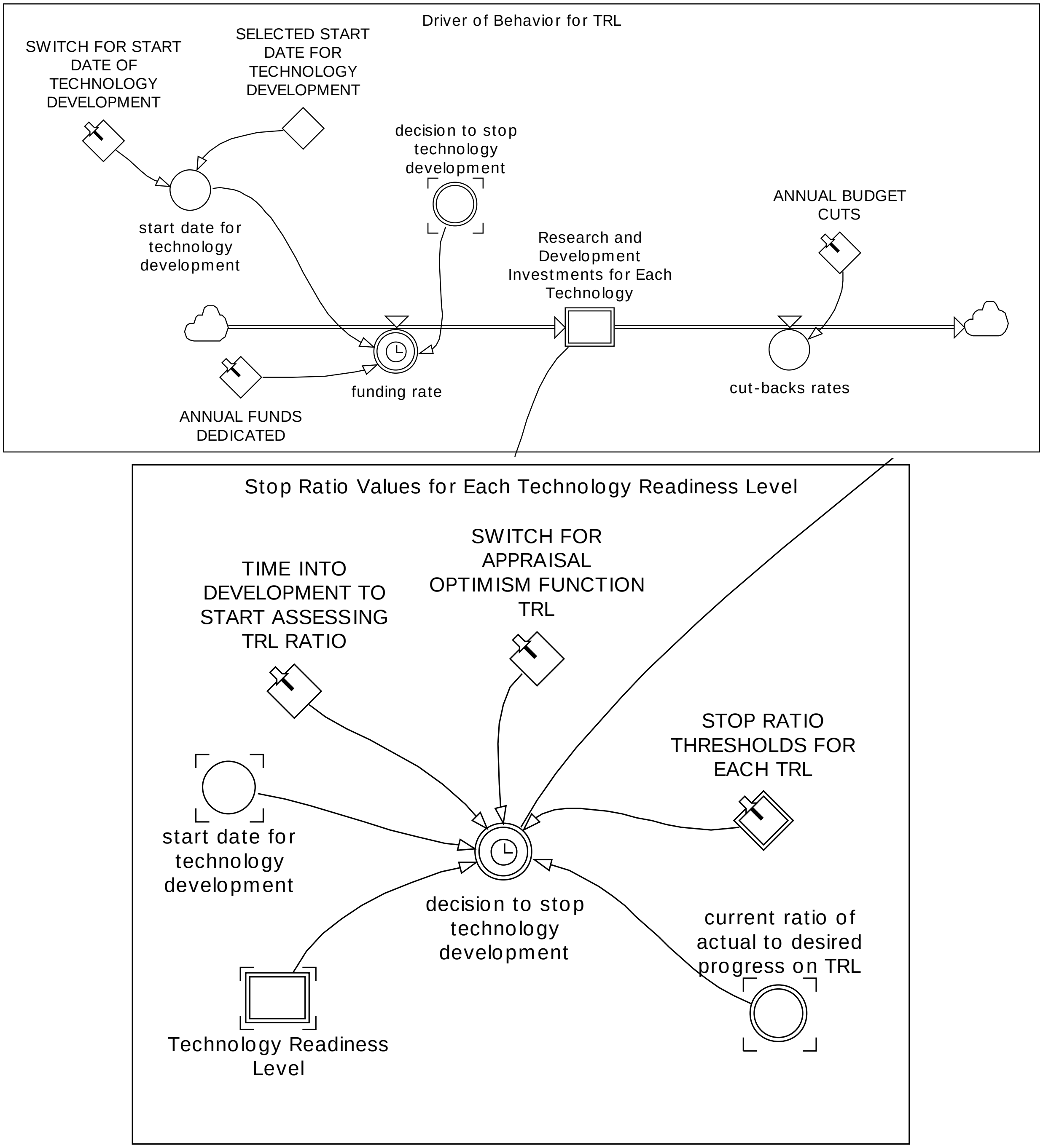

Figure A1c. The Core Components Detail for the Technology Readiness Level (TRL) sub-module (Driver).

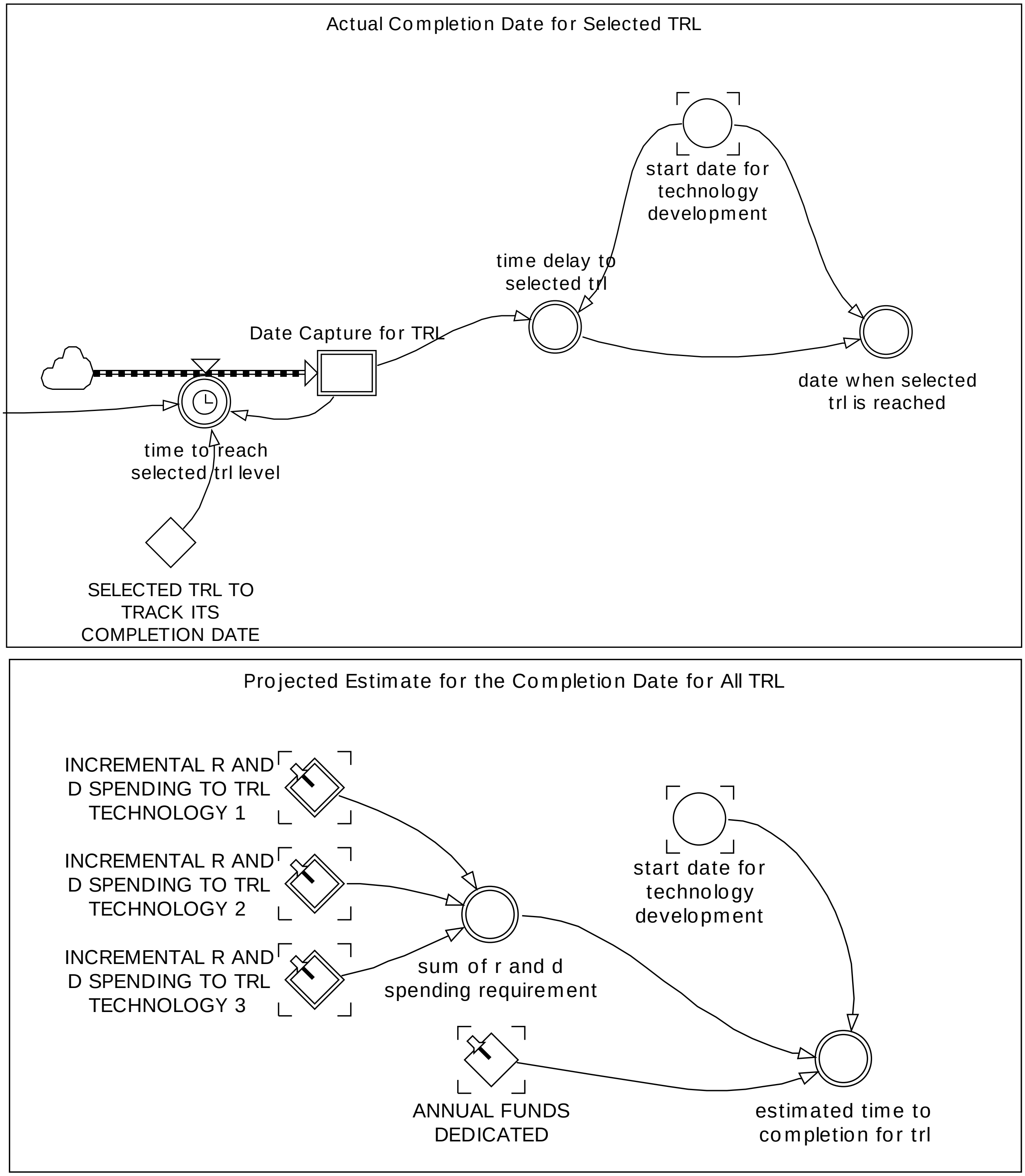

Figure A1d. The Core Components Detail for the Technology Readiness Level (TRL) sub-module (Completion Date).

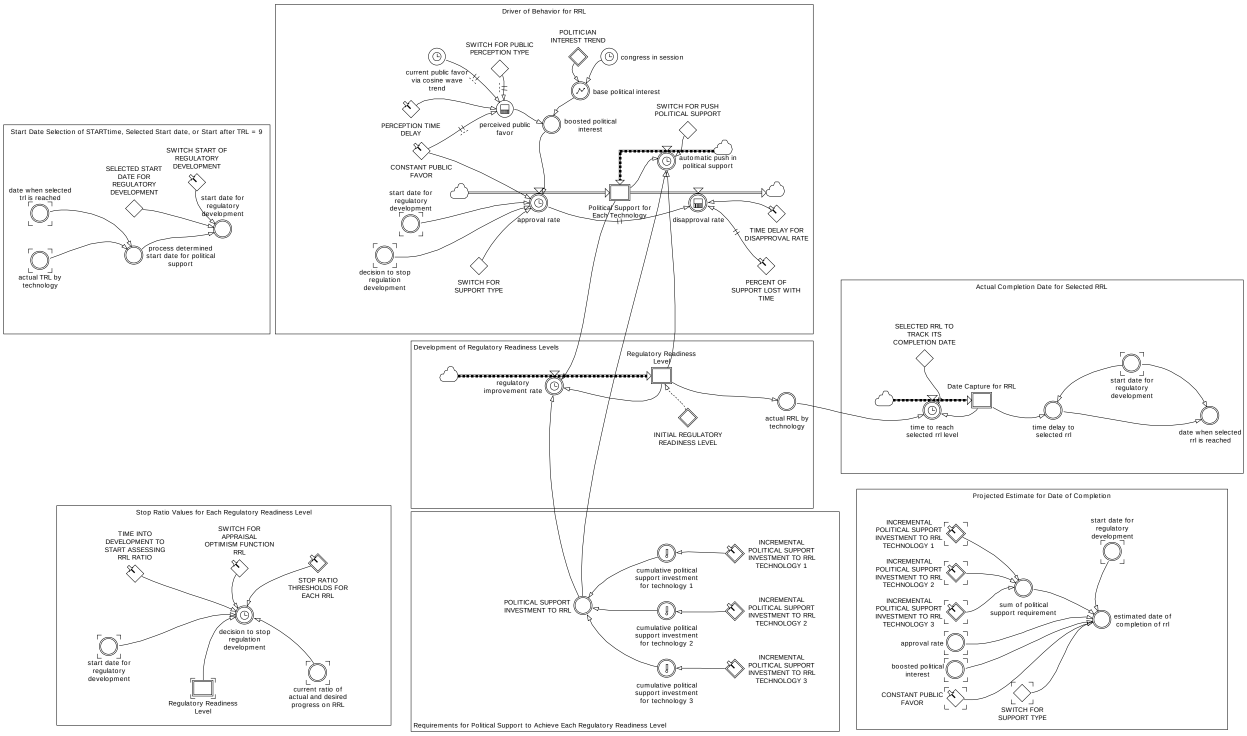

Figure A2a. The Overall View of the Regulatory Readiness Level (RRL) sub-module.

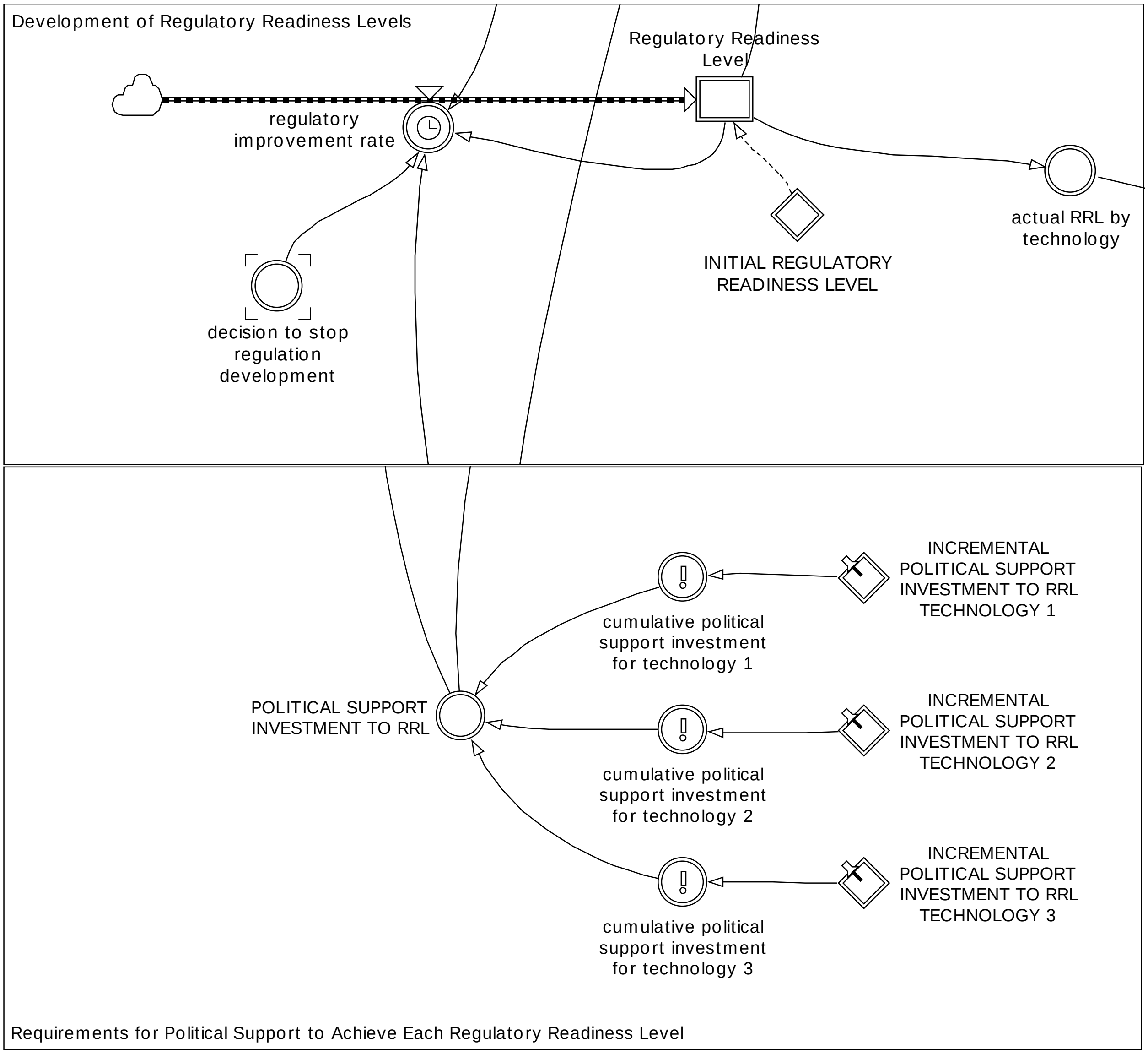

Figure A2b. The Core Components Detail for the Regulatory Readiness Level (RRL) sub-module.

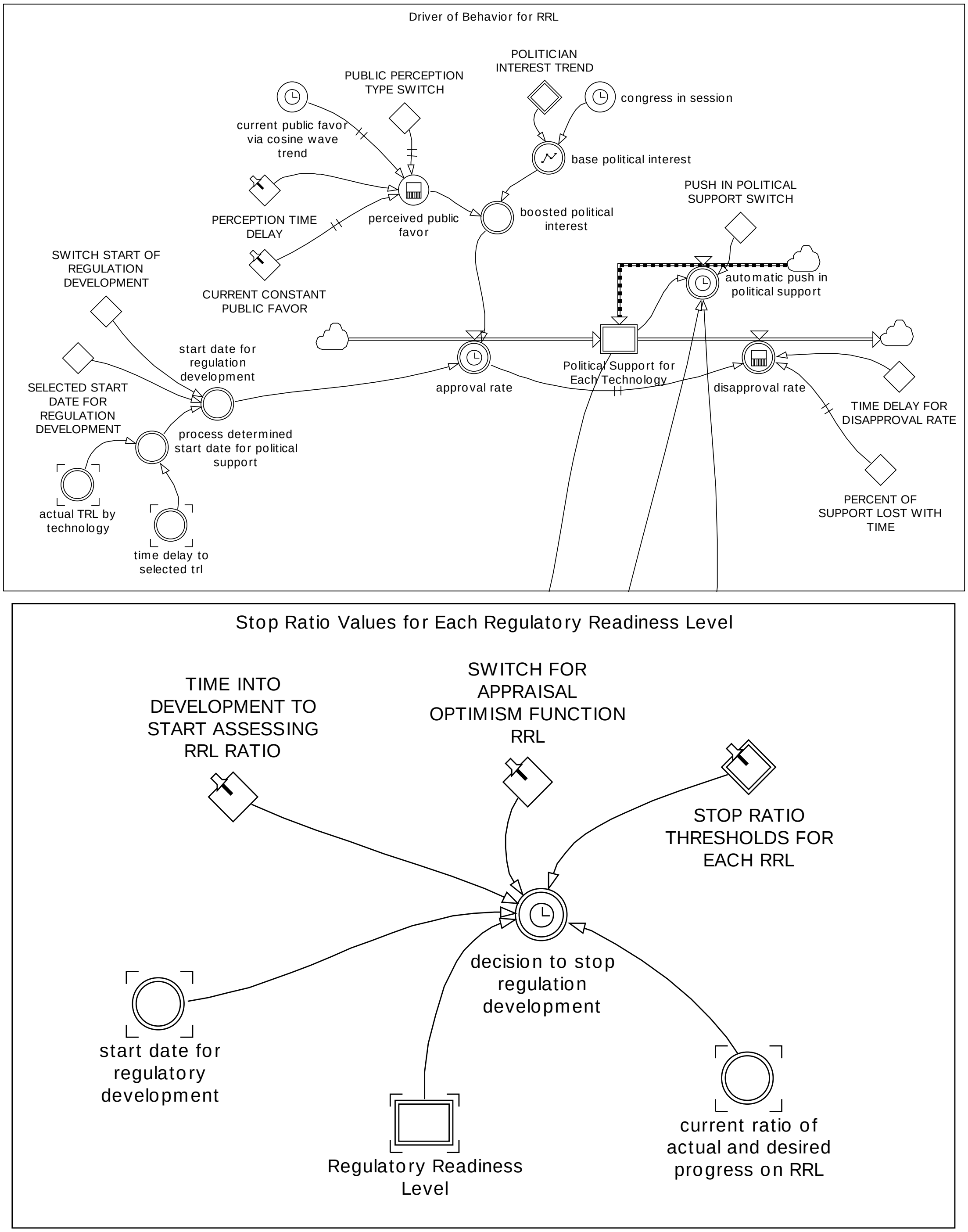

Figure A2c. The Core Components Detail for the Regulatory Readiness Level (RRL) sub-module (Driver).

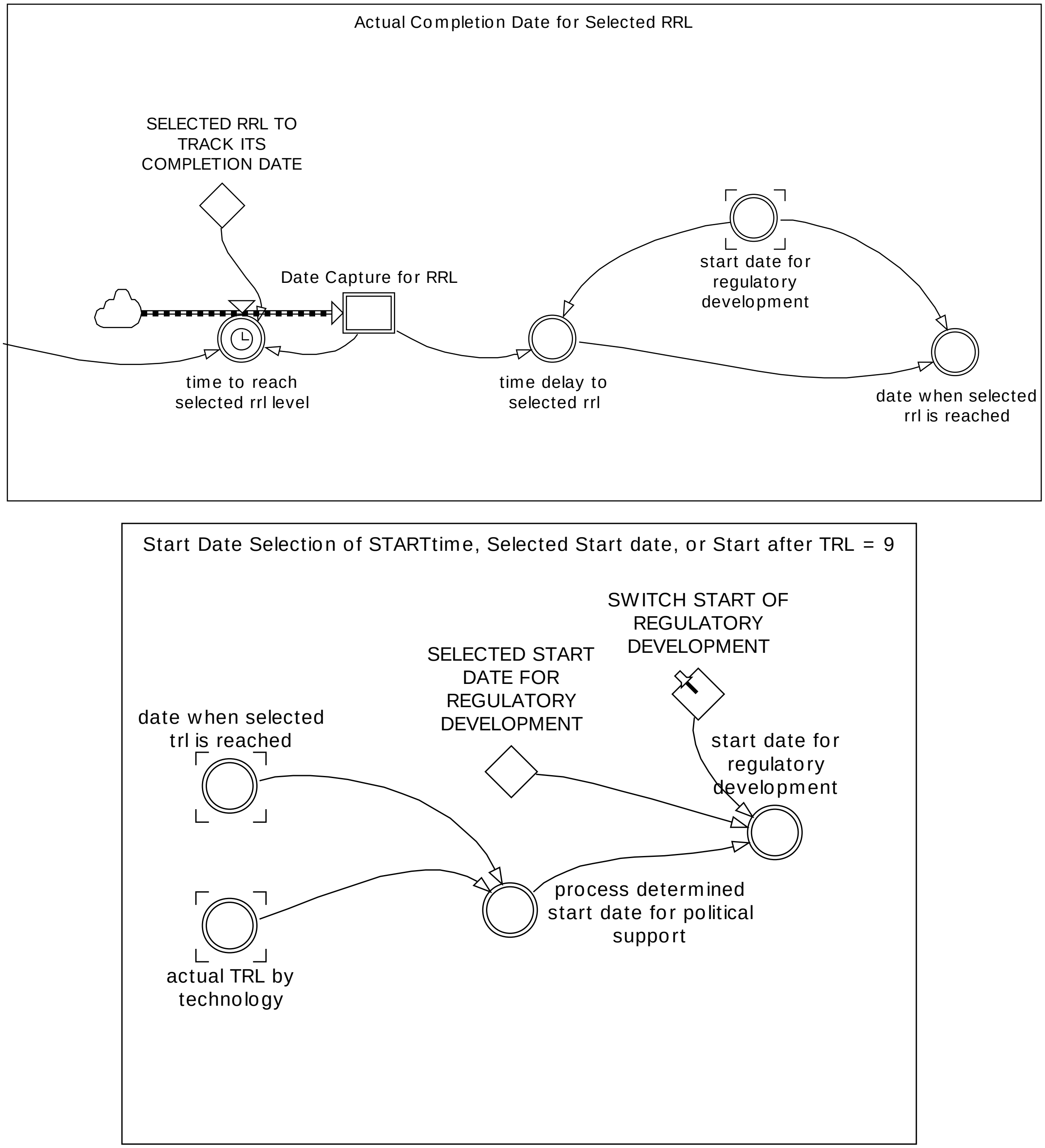

Figure A2d. The Core Components Detail for the Regulatory Readiness Level (RRL) sub-module (Completion Date).

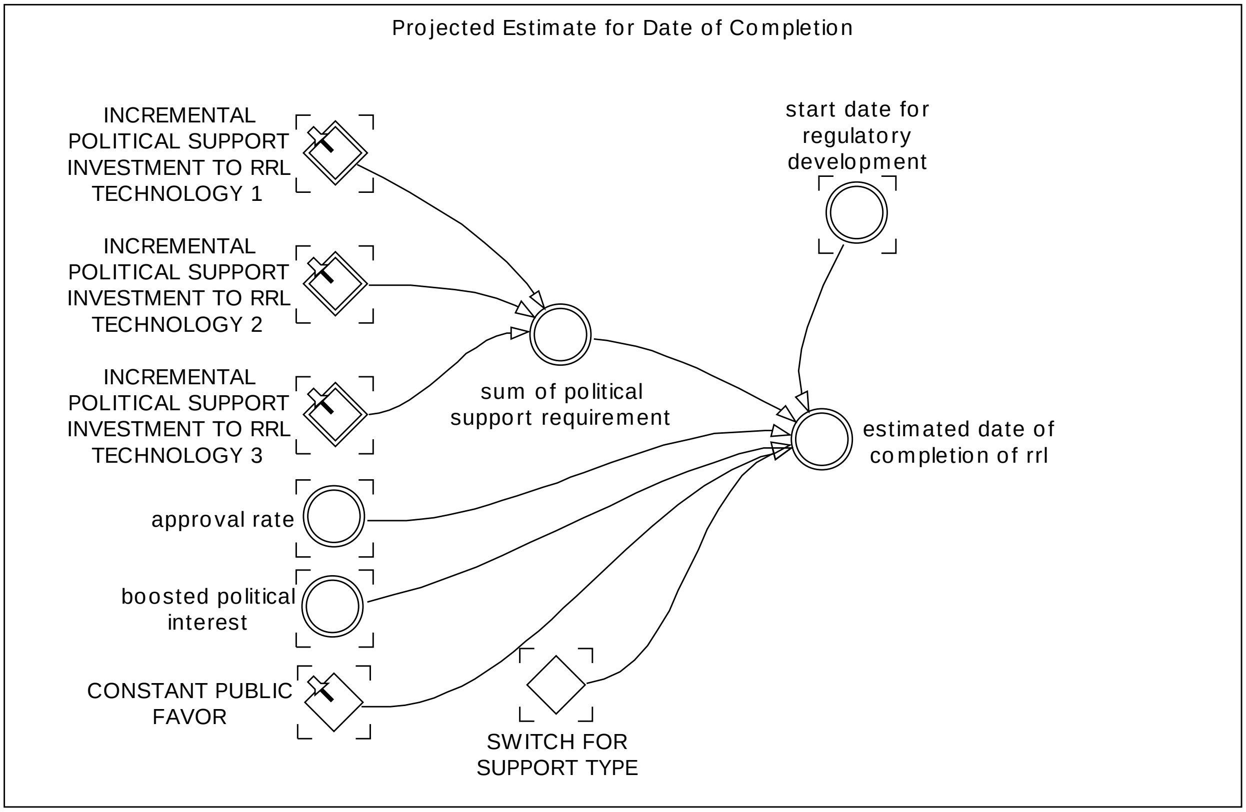

Figure A2e. The Core Components Detail for the Regulatory Readiness Level (RRL) sub-module (Estimate Date).

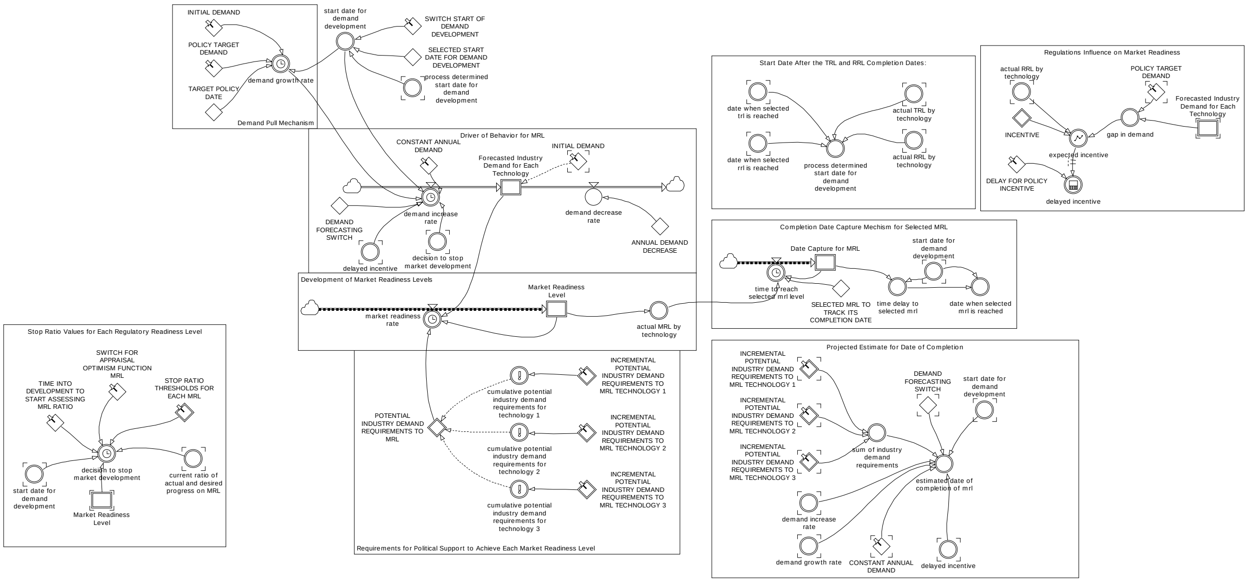

Figure A3a. Overall View of the Market Readiness Level (MRL) sub-module.

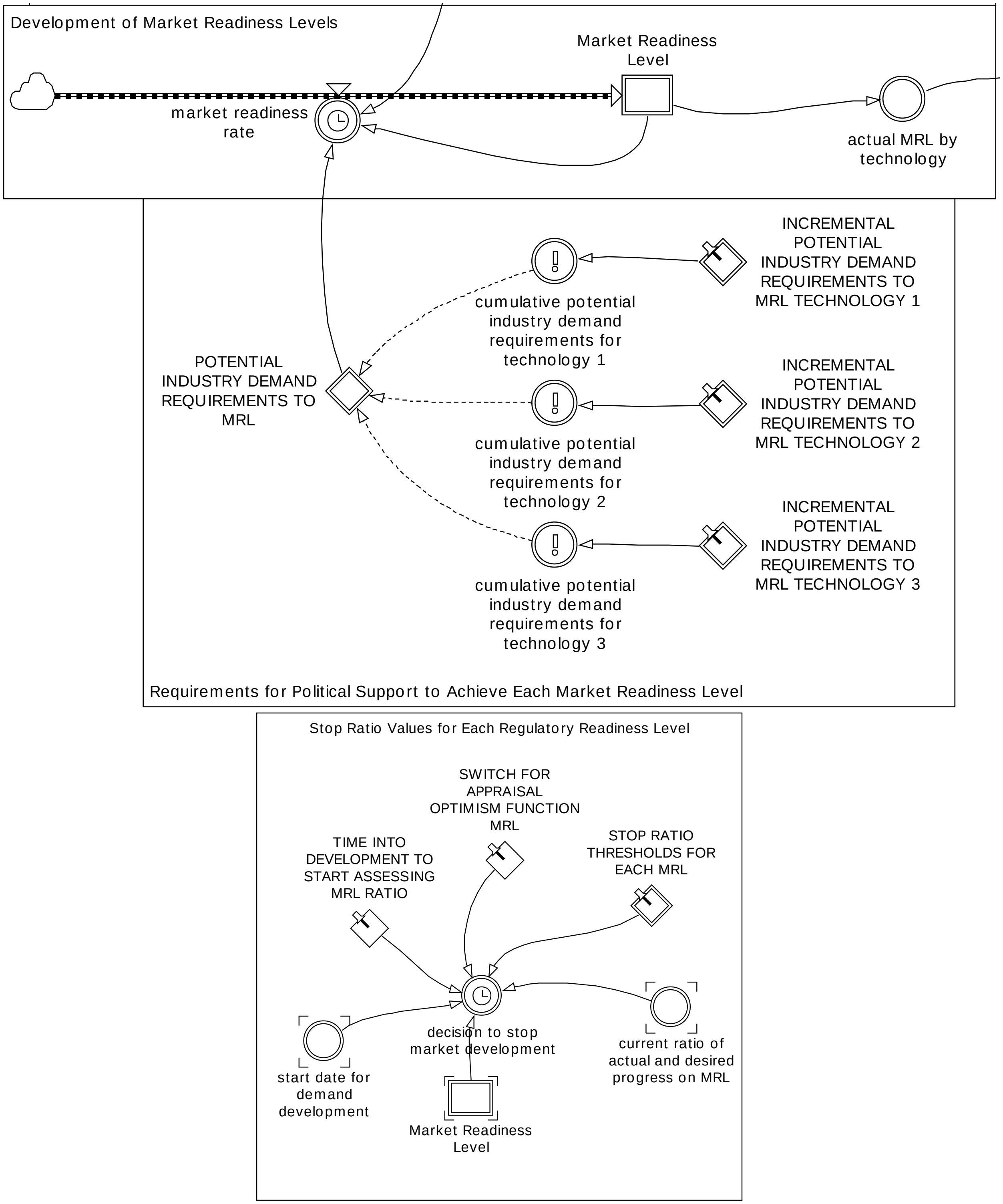

Figure A3b. The Core Components Detail for the Market Readiness Level (MRL) sub-module.

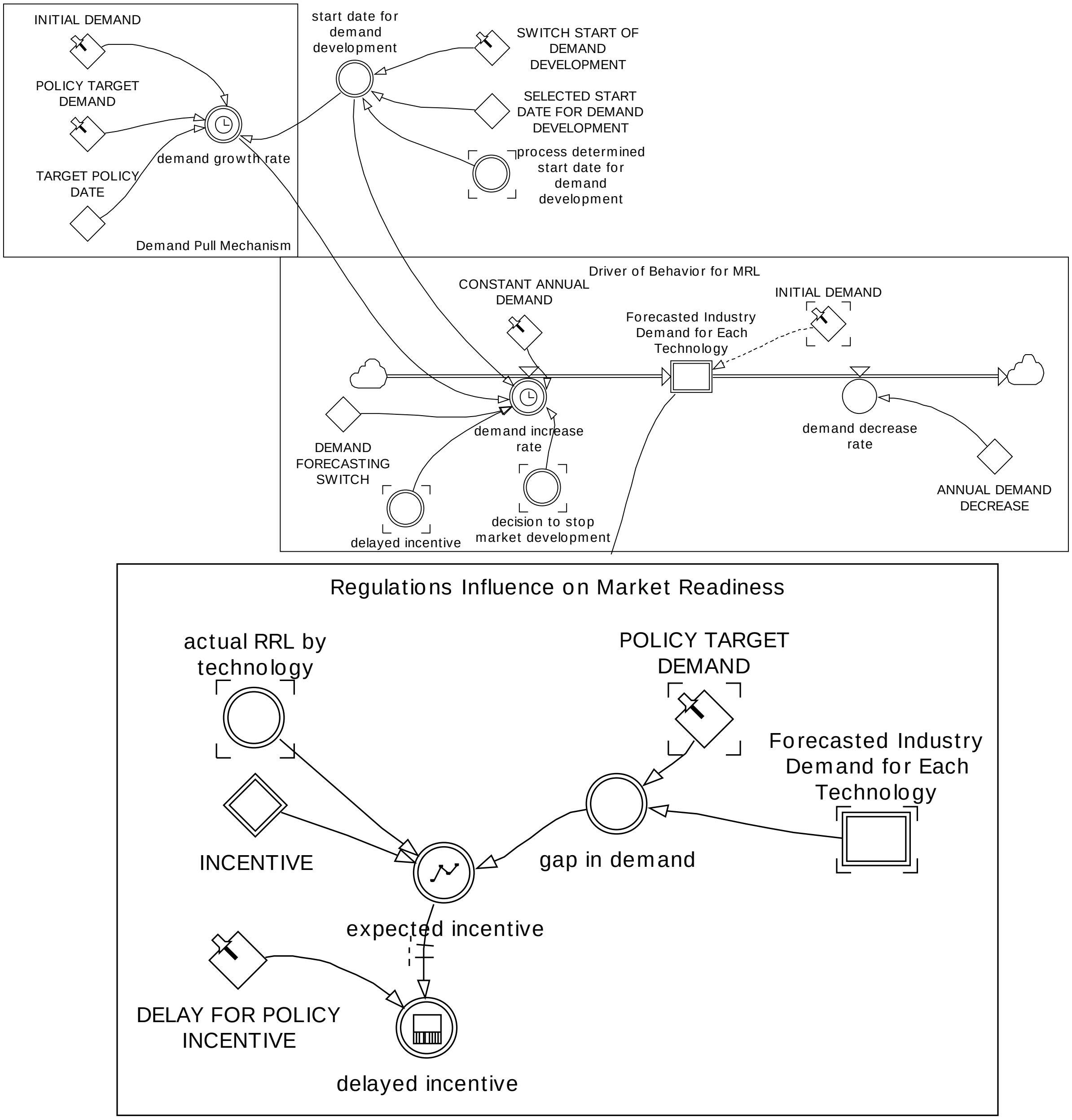

Figure A3c. The Core Components Detail for the Market Readiness Level (MRL) sub-module (Driver).

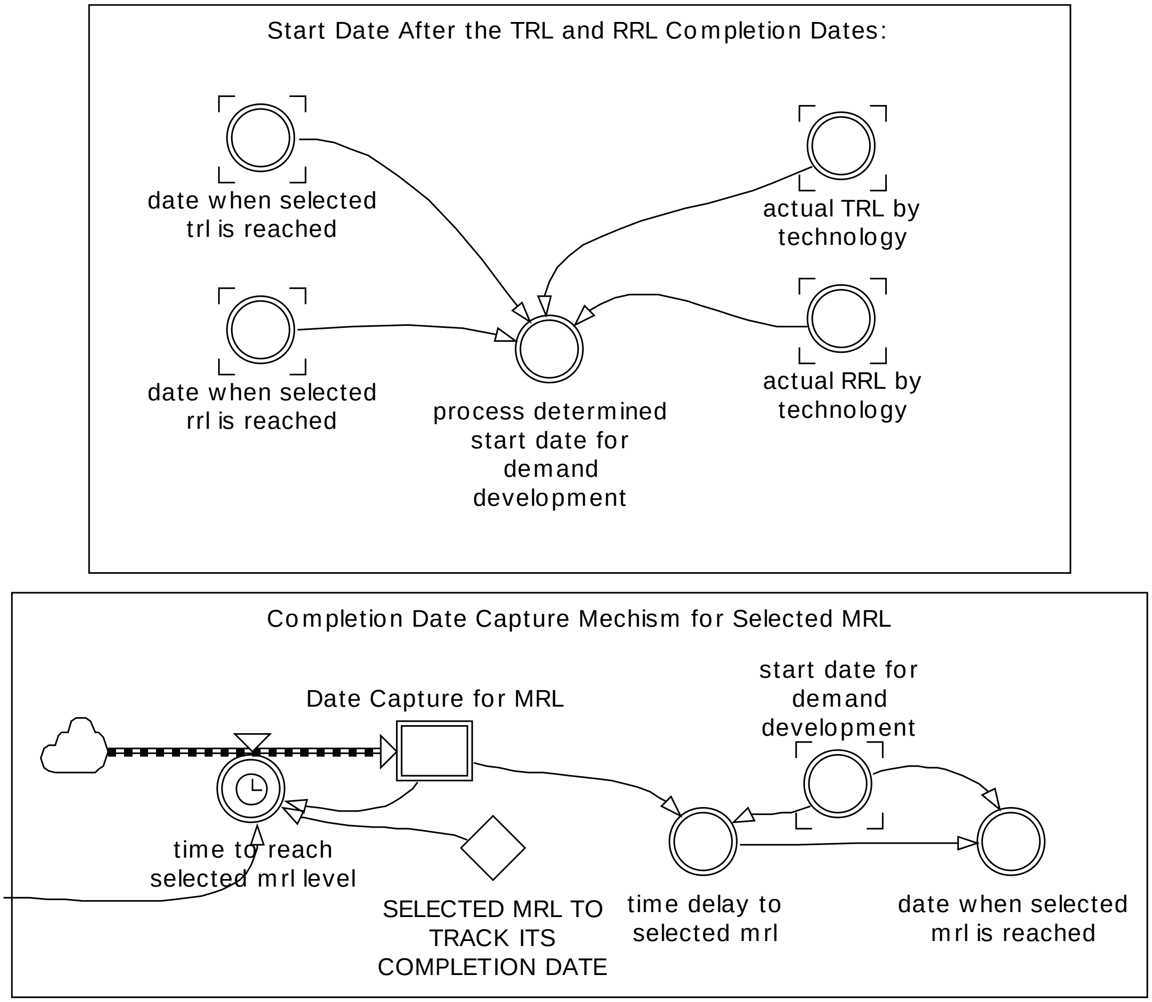

Figure A3d. The Core Components Detail for the Market Readiness Level (MRL) sub-module (Completion Date).

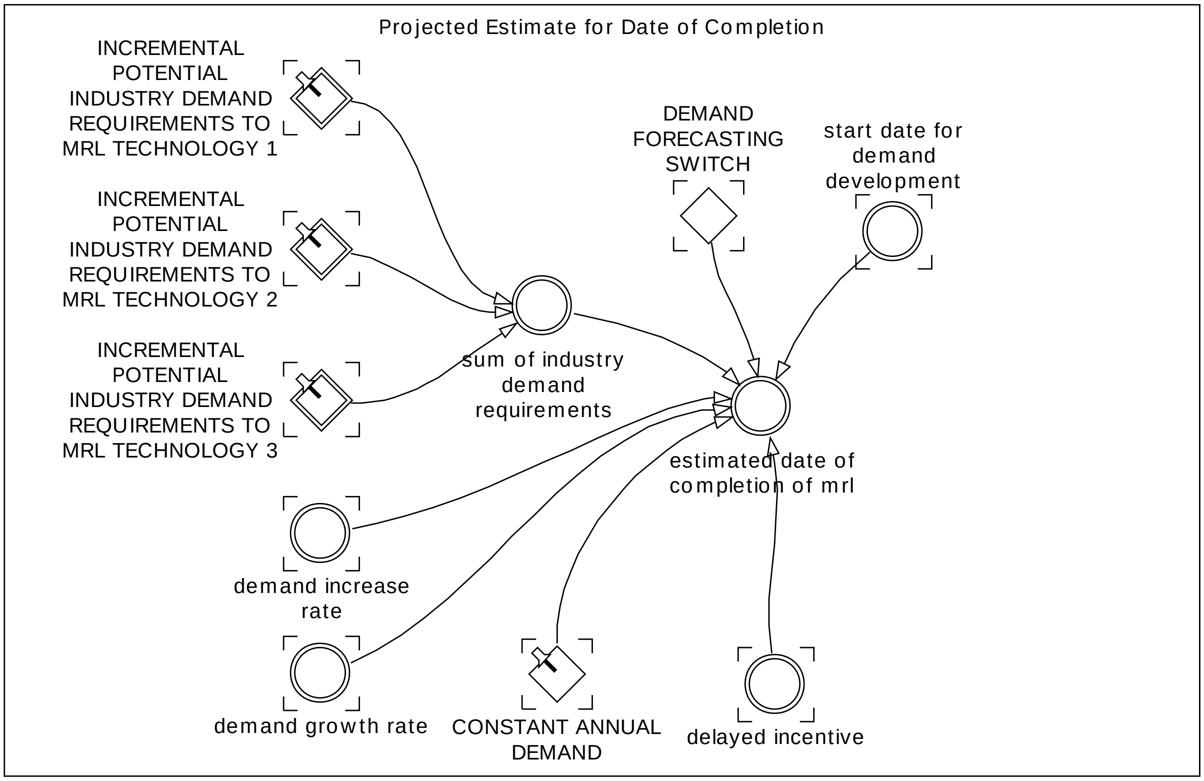

Figure A3e. The Core Components Detail for the Market Readiness Level (MRL) sub-module (Estimate Date).

APPENDIX B

Readiness Level investments

$$\boldsymbol{RL} = \iint_{\mathbf{1},\mathbf{1}}^{\boldsymbol{l},\boldsymbol{n}} (\boldsymbol{F} - \boldsymbol{D})\boldsymbol{dt}$$

Where:

RL = readiness level [TRL (technology level), RRL (political unit), MRL (market unit)]
F = rate of increase [TRL (USD/yr), RRL (traction unit/yr), MRL (investment unit/yr)]
D = rate of decrease [TRL (USD/yr), RRL (traction unit/yr), MRL (investment unit/yr)]
l = number of levels
n = number of technologies

Readiness Level threshold and increase

$$cl_l = \left\{ \begin{matrix} cl_{t,l} = 1, \;\; if\ cl_{t-1,l} = 0\ and\ RDI_t > \ RDI_l \\ cl_{t,l} = 0, \;\; if\ cl_{t-1,l} \neq 0\ and\ RDI_t > \ RDI_l \end{matrix} \right\}$$

Where:

cl_l = Current readiness level
$cl_{t,l}$ = Current readiness level at time t
RDI_l = Research and Development Investment threshold for level l [TRL (USD/yr), RRL (traction unit/yr), MRL (investment unit/yr)]
RDI_t = Current Research and Development Investment at time t [TRL (USD/yr), RRL (traction unit/yr), MRL (investment unit/yr)]

Ratio of actual readiness level achieved to appraisal optimism (expected) level

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

Where:

AT = actual technology level
AO = appraisal optimism or expected technology level
n = number of technologies
t = time

Decision to stop technology development

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

Where:

AT = actual technology level
AO = appraisal optimism or expected technology level
n = number of technologies
t = time

NOMENCLATURE

CAFE	Corporate Average Fuel Economy
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
TRMsim	Technology, Regulatory and Market simulation 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

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