Boom and Bust Cycles in Wind Energy Diffusion Due to Inconsistency and Short-term Bias in National Energy Policies

Katherine L. Dykes[1]
John D. Sterman
MIT Engineering Systems Division

Common knowledge in the wind industry pinpoints inconsistent policy, such as the production-tax credit scheme in the US, as a key source for boom and bust cycles in the wind energy industry. This paper looks at the sources of the industry boom and bust via a system dynamics model for diffusion of wind energy technology. A model is developed through the combined use of theory and calibration to a set of comparative national and state-level cases. The formulated model captures the effects of inconsistent policy for different historical scenarios of nations and states. Finally, the paper demonstrates through model simulations how short-term bias can harm the long term development of the industry by perpetuating these boom and bust cycles.

Keywords: Wind Energy, Diffusion, Renewable Energy, Technology Policy, Policy Incentives, System Dynamics

Introduction

Despite over 100 years of technology development, Wind Energy Conversion Systems (WECS) are still often seen as a novel electricity production technology. WECS were developed for electricity production in the late 1800s and enjoyed widespread use for rural applications by the 1920s. Then, the centralization of electricity production in the mid 20th century progressively led to discontinuation of wind energy for electricity applications for all but the most rural areas. The oil crisis reversed this trend and fostered a new era of innovation and diffusion of the technology. However, a stable and sustainable wind industry did not blossom immediately. Resistance from traditional vertically integrated utilities as well as the high cost of wind energy were impediments to growth of the sector. A wide variety of national policies and laws were enacted to invoke change in the electric utility sectors across the developed world and to allow for the development of wind energy and other non-oil electricity generation technologies. Certain countries, such as the US, sought to create a more competitive electricity market for energy. The *Public Utility Regulatory Policies Act* of 1978 was the first in a wave of federal legislation seeking to deregulate the electricity market and to incentivize non-oil based forms of electricity production (Gipe 1995). On the other hand, many European countries with more centralized governmental control over their electric sectors introduced mandates for change. For instance, France aggressively moved towards nuclear energy for new electricity generation plants. Other countries, such as Denmark, initially promoted nuclear power but found strong resistance from the public. This led them to negotiate a path for reform directly with their utilities and this resulted in investment subsidies and brokered power purchase deals for wind energy including a "100 MW agreement" of 1984 (Van Est 1999).

[1] Bldg. E62-367, 77 Massachusetts Avenue, Cambridge, MA 02139, dykesk@mit.edu

Despite these bold historical initiatives, changing policy landscapes for wind energy have been in general been unstable. In the mid-1980's support for WECS technology waned and the industry experienced cases of widespread bankruptcy both in the US and Europe. Few companies survived during this period and those that did, predominantly in Denmark, relied on substantial federal support for continued operation (Van Est 1999). In the subsequent decade, due once again to renewed policy support for wind energy, development rebounded in many European countries and eventually the US and beyond. Below is a chart of global wind installations as well as country specific installations for the US, Denmark, Germany, Spain and China among others. While the installations on a country level have been inconsistent, worldwide diffusion of wind energy has increased somewhat steadily over the last 30 years.

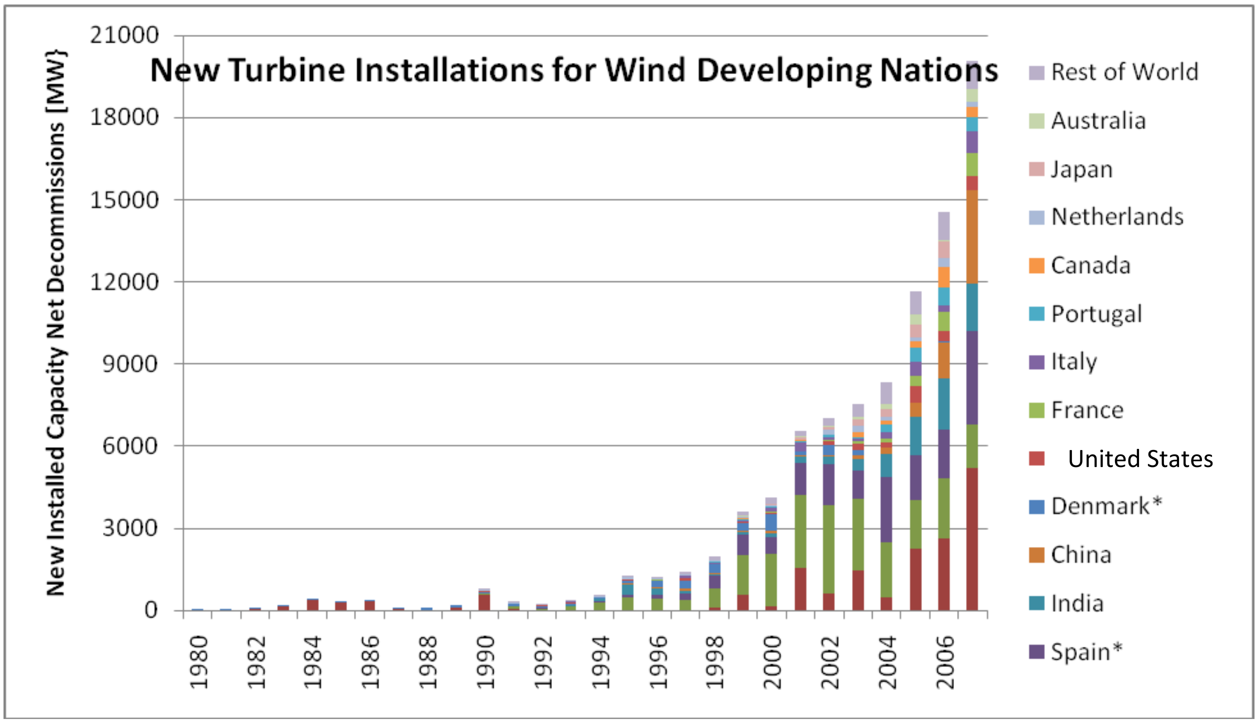

Figure 1: Global and National Wind Diffusion Levels (the Wind Power Net 2009, Eco Indicators 2009, IEA 2009)

Some would argue that the industry today has finally become self-sustaining. At the same time, the wind energy sector still relies upon considerable government support. Public policy that advances a country's development of emerging technologies may lead to a comparative advantage in economic sectors that contribute significantly to GDP growth. On the other hand, if those same policies are inconsistent over time, attempts to build strong competitive positions may in fact be slowed or even stopped. For many veterans of the boom-and-bust market for alternative-energy technologies that followed the 1970's oil crisis, public policy is viewed with an understandable amount of skepticism. In the past, public policy, via incentive programs and research funding, helped the US develop an early advantage in these markets. However, such proactive policies were essentially removed from the mid-1980's through the late 1990's and this led to the bankruptcy of not just the US but the international wind energy industry. On the other hand, more consistent policy in Europe, especially Denmark, allowed these countries to leap-frog the US both in terms of insta. Below is a graph of wind turbine installations in relation to country of origin of the manufacturer:

Figure 2: Global wind Installations by Manufacturer Country of Origin

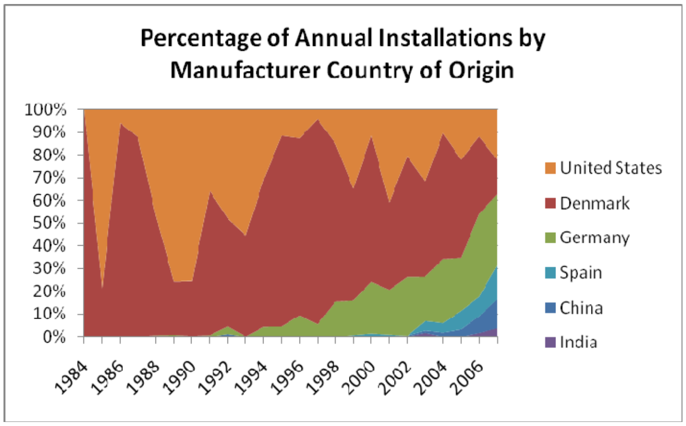

Figure 2: Wind Installations by Manufacturer Country of Origin (Wind Power Net 2009, Winds of Change 2009)

The history and current status of the wind energy industry is no doubt complex (Dykes 2010). A wide variety of arguments have been made regarding the influence of policy over technology development, on adoption trends and over firm behavior. This paper presents a system dynamics model that reflects the historic performance of different countries' wind energy markets. In so doing, the impact of policy on the respective development of different national markets for wind energy is investigated along with the development impacts on the industrial base. Once the model has been calibrated to a set of historic cases, the paper then tests a set of hypothetical policy scenarios on wind energy adoption. The results will provide insight and understanding into the dynamic relationships between policy, technology adoption, and industry development in order to guide national policy-making strategy for future development of the wind energy sector.

Theory – Diffusion Models and Wind Energy

Before formulating the model, a theoretical understanding of technology diffusion is critical. This topic has long been of interest to social scientists and theory in the area is substantial. In general, there are two basic types of diffusion models. The first is a "threshold model" that focuses on economic factors as the main determinants for the adoption of a product or technology (Griliche 1957). However, the explanatory power of such models was found to be wanting in some cases, and eventually these models were supplanted in many cases by models that took into account social factors such as shared information, experience and influence. These "social models" of diffusion relied on social contagion as the main factor influencing adoption (Bass 1969, Rogers 1995, Ryan and Gross 1943, Mahajan 1985, Mahajan 1990). The basic "Bass model" of diffusion has become especially prominent and well known in marketing and has been used substantially in prior System Dynamics studies (Homer 1987, Sterman 2000, Milling 2001). Finally, another category of diffusion models brings together the economic aspects of threshold models and the social aspects of the Bass diffusion models. These "mixed-influence models" are particularly well-suited for analysis using system dynamics since the combination of economic and social effects can be well-modeled using additional feedback relationships affecting adoption behavior (Sterman 2000, Milling 2001, Granovetter 1985, Weil 1998).

In particular, for wind energy adoption, the dual socio-economic influence is important for technology adoption. However, a detailed network representation such as is used for many consumer product diffusion models is likely unnecessary. A few such models have previously been developed specifically to look at wind energy adoption (Pruyt 2004, Dyner 2006). The first model by Pruyt was designed in order to critique a spreadsheet model of diffusion that was created outside of the system dynamics framework and thus ignored key feedback relationships in the system. The second model by Dyner (2006) is a diffusion model for wind energy but takes into account a much more broad set of relationships related to the overall electricity market at the expense of detailed modeling for the wind industry in particular. The importance of the combination of the industry capacity aspects of the Pruyt 2004 model, the endogenous electricity aspects of the Dyner 2006 model, and the learning curve effects in both models will be discussed in more detail in the model formulation section of this paper. As a final comment, there is another class of models, capacity expansion and electricity planning models, which also look at the joint technical and economic needs of the electricity system to look at overall long term planning for the electricity sector. There are many examples of system dynamic models developed in this space but are beyond the scope of this particular paper (Ford 1996, Ozdemeir 2002, Vogstad 2002, Dyner 2006, Karstad 2009).

Methodology

Unit of Analysis

A system dynamic model can involve a large number of variables and functional relationships. However, some variables are more critical than others in terms of influencing the model scope and formulation. In this case, the primary "dependent" variable of interest is the number of installed turbines for a given system case. For models relating to the electricity grid, there is difficulty defining the boundary for separating out the global system into different cases. For instance, US federal policy affects wind energy adoption nationally but so does policy at the individual state and locality. The electric grid, on the other hand, is typically seen as a regional system in terms of generation and transmission assets. In Europe, Denmark's national policies drive wind development for the entire nation-state but at the same time, its electric grid (and thus wind generation assets) are tied into the larger Nordic Power Pool combined especially with the Norwegian and Swedish hydro and gas systems. For the purposes of this research project, the system boundary for a specific case is defined as the state boundary (US state or European national) and wind generation assets are counted if they occupy land within that state since most significant policy levers are applied at this level.

Case Selection and Data Collection

Of the 50 states in the US, 29 have significant wind installations (defined as greater than 10 MW installed in the state). In Canada, 9 of the 12 provinces have significant wind installations. Beyond these two countries, there are at least 50 countries worldwide with significant wind installations. Each state has a different set of policies that have or have not been applied in order to affect renewable energy development in general or wind energy in particular. In selecting cases, a cross section of countries with different levels of wind energy capacity and policy is preferable. Of the 89 combined states and nation-states, 64 have capacity installations of over 100 MW, 24 have over 1000 MW and just 3 (not including the national US and Canadian borders) have over 1 GW of installed capacity. The policy types also vary across the different states. Below is a categorization of sites based on various policies implemented.

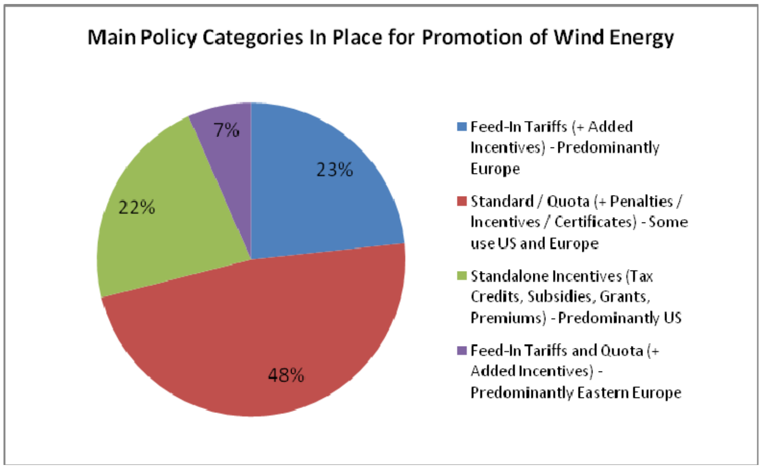

Figure 3: Pie chart of Policy Distribution among States (IEA 1997, GWEC 2008, DSIRE 2009, AWEA 2009)

For case selection, a stratified sample with systematic case selection was used (Babbie 2004) along with a multiple time series research method (Campbell 1963). Given the nature the study, the multiple time series approach is the only available research design that promotes full internal experimental validity (Campbell 1963). A cross section of states serves for model calibration and another for validation. While it would be convenient to select cases on the basis of installed capacity, this variable is directly related to the dependent variable of interest: installed turbines. Thus, the stratified sample groups were created on the basis of policy type to ensure that cases were selected from each policy group. Samples were selected by systematic selection of cases within each policy category excluding those cases where policies were just recently implemented or where sufficient data was unavailable on the characteristics of the wind potential, installations or economics. For a multiple-time series type of experiment, external validity can be limited. However, by using a wide variety of cases for model formation and validation, the possibility for external model validity and building general insight is possible. The following line-up of calibration and test cases were identified through the sampling process:

Table 1: Cases for Calibration and Testing

Policy Type	Cases
Feed-in Tariffs	Germany, Spain, Portugal, Denmark
Standard/Quotas	Colorado, Illinois
Incentives	California, Idaho

Data collection used a variety of sources. Most aggregate data of interest were available from large statistical commercial, national and international databases. The policy information was obtained through the review of various secondary publications including academic article, national and international reports. Some simplifying assumptions were necessary to convert the data collected into usable model parameters and these are explicitly specified where used. More information on the specific variables and data collection will be discussed in the model formulation section.

Method of Analysis

As mentioned before, system dynamics is an appropriate modeling framework for analyzing complex diffusion process such as those involved for wind energy. Diffusion theory and associated models were selected over capacity expansion theory and models in order to explicitly focus the study on of the detailed case of wind energy. In order to formulate the diffusion model in system dynamics, theory and prior work was applied where applicable. Traditional steps in system dynamics modeling were employed including problem articulation and formulation of a dynamic hypothesis, formulation and model testing, and finally policy design and evaluation (Sterman 2000).

Model Formulation

Theoretical Derivation – Key Assumptions

As mentioned previously, the basic theoretical framework used in this study concerns the combined mixed-influence model of diffusion using both economic and social drivers to adoption. In order to simplify the scope of the study and keep the model tractable, a few important assumptions were used:

1. Low wind penetration as a function of both installed capacity and electricity production
2. Limited ability to transfer capital assets across state boundaries (especially between Europe and the United States)
3. Technology evolution / innovation is a global phenomenon independent of any individual state activity
4. And tangentially, learning curves except for economies of scale due to increasing turbine size are negligible in terms of governing the costs of wind energy technology

While these assumptions do break down for certain cases and under certain conditions, they are generally reasonable for the historical development of the industry. Exceptions will be discussed when they are relevant to particular cases.

Theoretical Derivation – Model Development

Having defined the scope of the model, the general dynamics of interest can be developed as shown in the below causal loop diagram.

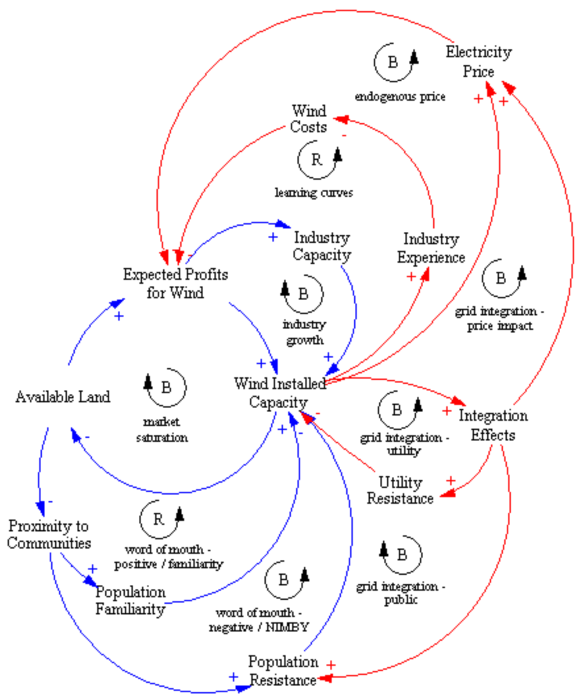

Figure 4: Full Industry Level Causal Loop Diagram for Wind Diffusion

The primary Bass, or social influence, dynamics of the model include the population familiarity and population resistance. As wind energy is first introduced, there is an intrinsic resistance to the unknown that is mitigated as more wind is adopted and positive word of mouth concerning its viability spreads. However, there is a secondary social loop regarding the encroachment of wind nearby population dense areas and, consequently, an associated NIMBY resistance / negative word of mouth develops. The primary driving loops on the economic side include the availability of land and the associated wind resources of that land. Associated with these economic drivers are cost of wind energy, electricity price and all the associated dynamics of economies of scale, scope, learning curves, and more. In addition, the system integration influence on both electricity price and system operations are demonstrated. The more wind capacity on the system, the higher the electricity price due to the system costs associated with the intermittent resource as well as direct costs for the higher price of wind energy relative to traditional electricity generation technologies.[2] There is also a build-up of resistance by utilities

[2] The relationship here is actually more complex. At low wind energy levels where installation is profitable, wind energy in a system can actually lower the electricity price since there is an offset in the fuel costs needed for other electricity generation assets. During times of high volatility of fuel costs, wind energy can be a substantial buffer against the costs associated with that voltatility.

or system operators who have to manage the system integration issues and from the public if the installed capacity is high enough to affect overall system performance.

Returning to the case specific model, however, the goal of this paper is to look at the impact of specific nation and state level policies on wind energy adoption. The main dynamics (blue loops) for this simplified case-level model include: resource use, industry capacity, and population acceptance / resistance. For the purposes of the case-specific model, the influence of system integration, technology evolution and endogenous pricing are removed. Even in the simplified form, the model already involves a number of complexities including various nonlinear relationships and feedback delays. The formal model and important functional relationships are described in detail in appendix A.

Case Study Calibration

For each case, a set of independent input and dependent output variables was collected. For input, the total land, distribution of wind resource (capacity factor), the maximum capacity factor, the electricity price profile, the population density and the wind-incentive policies and years of action were collected. Variables such as electricity price and policies that depend on time were obtained for the years 1975 to 2010 and normalized to be in 2009 USD.[3]

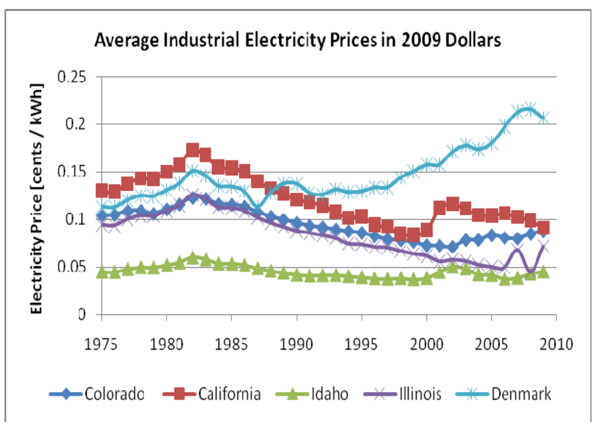

Figure 5: Electricity Prices (EIA 2009, Eurostat 2009, CPI 2009)

Interestingly, electricity prices over the last decades (post 1985 when oil prices returned to pre-crisis levels) have declined in real terms. On the other hand, in Denmark, prices have steadily increased. Without more data on prices for the rest of Europe it is hard to tell if the trend is directly linked to the growth of wind energy installations in Denmark over the same period. In general, increasing electricity prices would spur additional wind development unless public

[3] While, US information was obtainable for all the cases, European information especially regarding electricity price was more difficult. For Europe, only electricity prices for Denmark could be obtained for years prior to 2000 so these electricity prices were used as a proxy for the rest of Europe which could have introduced bias into the other European case-level models.

resistance increased due to the positive relationship between wind energy installations and electricity price.

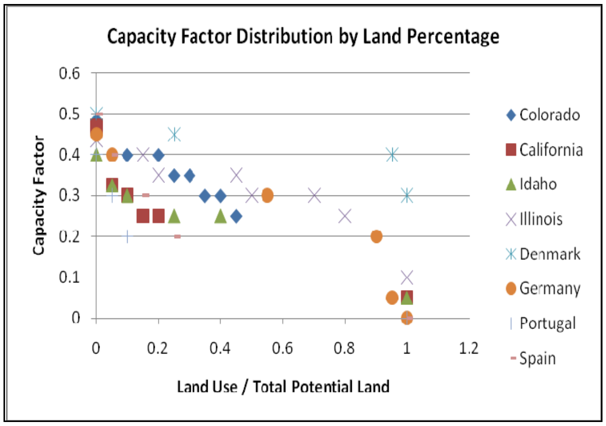

Figure 6: Capacity Factor as a Function of Land Use (NREL 2009, Wind Atlas 2009)

Simulation parameters were set to be the same in each case except for the input variables described for the electricity prices and capacity factor above as well as the policy measures and the land parameters as shown below.

Table 2: Case Input for Parameters of Interest

	Colorado	California	Idaho	Illinois	Denmark	Germany	Portugal	Spain
Land Area (m^2)	2.7E+11	4.09E+11	2.16E+11	1.46E+11	1.4894E+11	3.5E+11	3.54E+10	4.99E+11
Maximum CF	0.485	0.47	0.4	0.435	0.5	0.45	0.4	0.5
Policies	2004 RPS	1980-1985 Investment Subsidy, 2003 RPS	N/A	2007 RPS	1980/1984 100 MW, 1977 - 1989 Investment Subsidy, 1992 Feed-In Tariff removed in 2001, reinstated in 2007	1990 Feed-in Tariff	1999 Feed-in Tariff	2001 Feed-in Tariff
US Federal Policy	yes	yes	yes	yes	no	no	no	no

Simulations were run for the different cases in order to compare the main output parameters of number of installed turbines (annual and cumulative) and installed generation capacity (annual and cumulative). Selected examples for discussion are shown below and the remainder of the case data and simulations are shown in appendix B. The first case shown below is for Colorado in the US which passed legislation by ballot vote in 2004 to institute a Renewable Portfolio Standard. The standard requires compliance at various levels after 2007 and includes a tradable certificate market. The expected value of the certificates acts as a price incentive for wind energy development in the state. Data on certificates shows values for the certificates in compliance markets to be on the order of \$0.02 to \$0.05/kWh (EWEA 2009). As can be seen in the below charts, wind development is slow until 2004 with large increases in 2006 before the first year of required compliance to the RPS. The simulation also captures this strong growth trend after the year 2000.

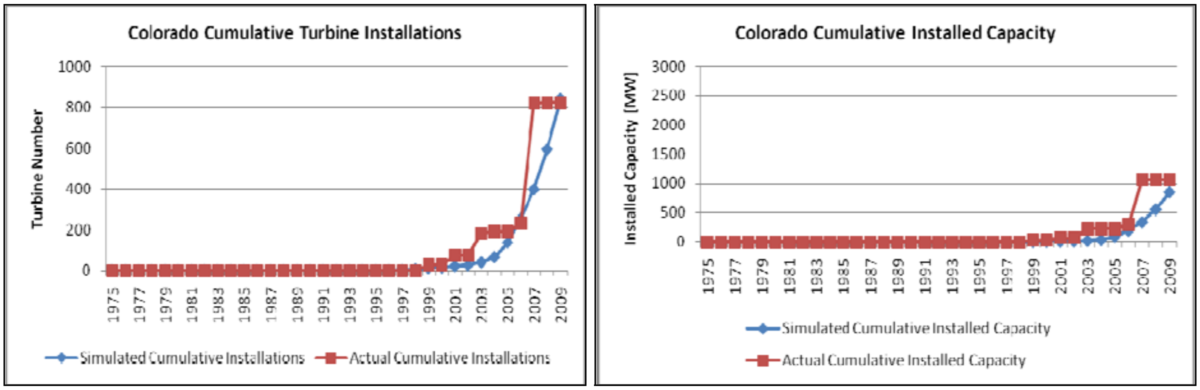

Figure 7: Cumulative Turbine Installations and Installed Capacity for Colorado - Simulated and Actual

The case of California involved a series of fiscal incentive programs and negotiated power purchase agreements with utilities in the early 1980s and then the institution of a RPS in 2003. The strong incentives in the early 1980s led to a boom in installations of modest sized turbines, many of which still operate today. The simulation captures some of the early development but not nearly enough to match the actual dynamics that occurred during that period, and so the early development is underrepresented and the later development overrepresented. This can be seen even more prominently in the graph of fractional installations of new turbines on a yearly basis where thousands of turbines were installed in the early 1980s during the "wind rush". The combined incentives at local, state and federal level caused unprecedented growth in the sector where even some non-working machines were installed to capture investment tax grants in particular (Gipe 1995, Van Est 1999).

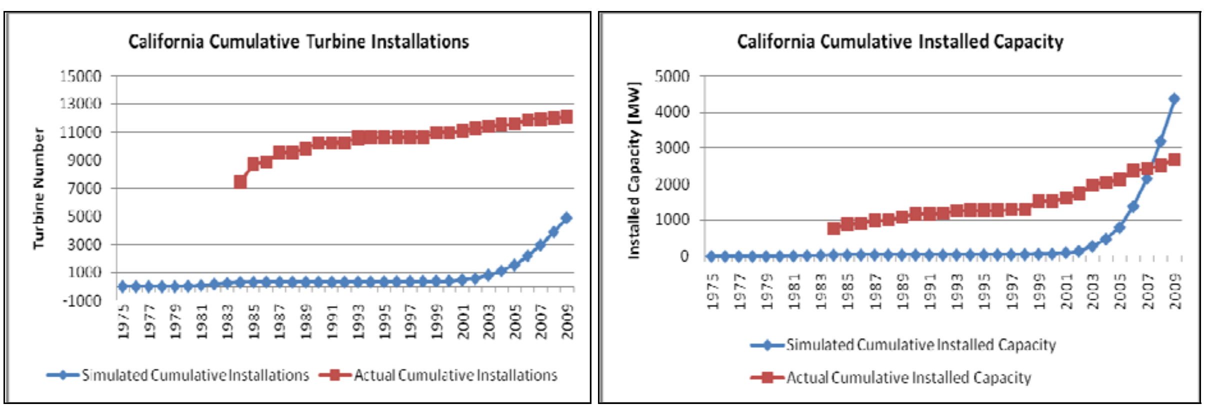

Figure 8: Cumulative Turbine Installations and Installed Capacity for California - Simulated and Actual

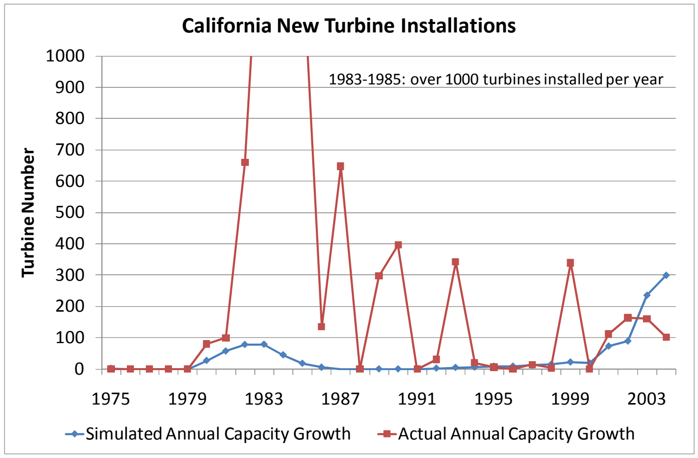

Figure 9: Fractional Installation of New Turbines in California

The case of Portugal involves the institution of feed-in tariffs in 1999 that essentially help wind compete on par with any other electricity generation technology in the mix. This causes a strong growth rate in the years after 2000 captured by the simulation. The growth rate in the simulation is slightly higher than the actual case which may reflect the inaccuracy of using the Danish electricity prices or other concerns. The percentage of electricity in Portugal generated by wind energy today is about 9% which means that some of the assumptions regarding an exogenous electricity price and ignoring dynamics related to system integration may be inaccurate.

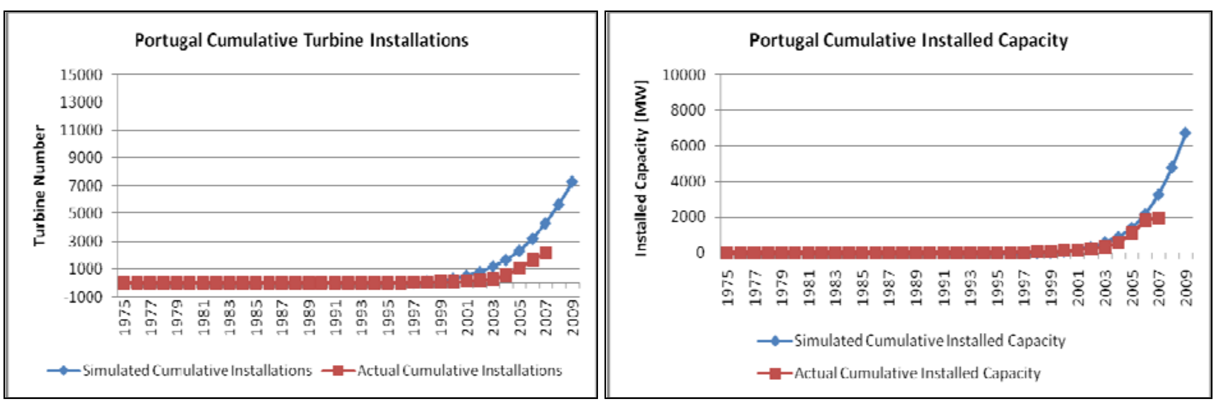

Figure 10: Cumulative Turbine Installations and Installed Capacity for Portugal - Simulated and Actual

The same issue holds true and is even more prevalent in the case of Denmark where several different incentive programs have been enacted since the late 1970s. From investment subsidies to negotiated power purchase agreements to research and development funding and finally a feed-in tariff program, Denmark has used an aggressive policy scheme to push domestic wind energy development. The model underestimates wind energy in the state after the 1980s. In particular, the feed-in tariff was established in 1992 and then removed in 2001 and reinstated in 2007. There is a flattening of growth associated with the tariff removal but also the influence of other feedback dynamics not captured in the state-level model such as integration effects.

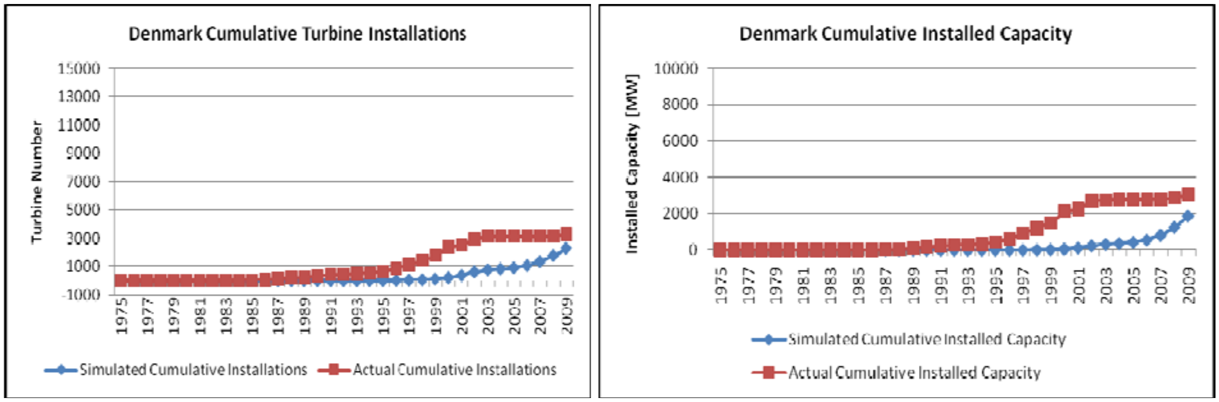

Figure 11: Cumulative Turbine Installations and Installed Capacity for Denmark - Simulated and Actual

The collection of simulations show that the general dynamics of wind energy dynamics are captured with some limitations. In particular, the effect of population dynamics is not sufficiently characterized as of yet in the model. In addition, the issues associated with system integration were explicitly left out of the study but as can be seen in the two European cases above, they are likely important if the model were to be applied for analysis of wind diffusion at levels higher than a few percent. With these caveats in mind, we now turn towards policy analysis for a generic case of wind diffusion.

Analysis and Results

In terms of defining a generic case for analysis, Spain is used for model parameterization. The results of the actual versus simulated installations and capacity are shown in the appendix B. Initial land, capacity factor, electricity price, and policy variables are set to those values obtained for Spain over the period from 1975 to 2000. A base case is generated through the elimination of policy effects – i.e. the development path that would have been likely had Spain not used various incentives during the last decade for wind development.

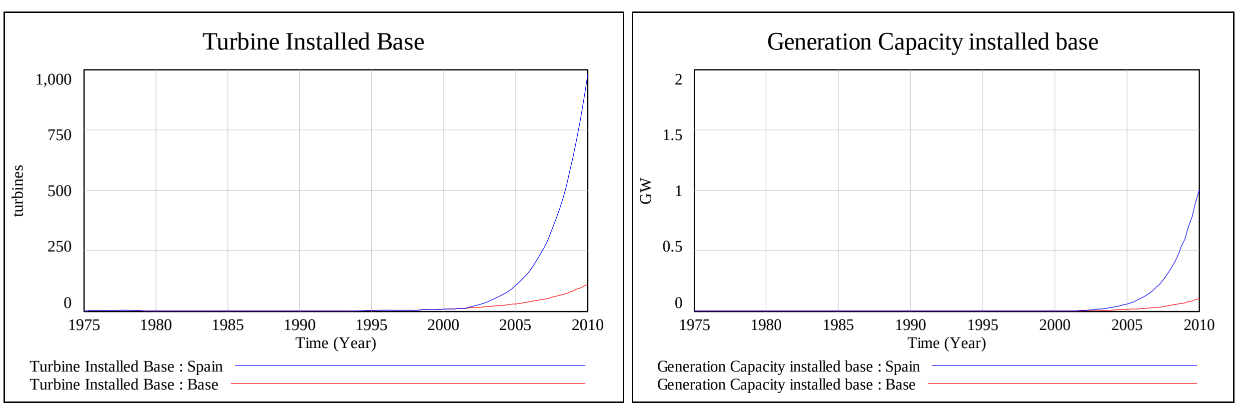

Figure 12: Turbine Installations for Spain and Base Case which excludes policy influences

As can be seen, the elimination of policy from the Spanish wind development scenario causes the installed base in wind energy to drop by roughly a factor of 10 in the years prior to 2010. This is consistent with general knowledge that wind development has historically depended on policy support from national and state governments. Having inspected the results historically, the continued impact of the different policy measures into the future requires some additional assumptions regarding technology improvement and electricity prices. For the purposes of this study, both are kept exogenous. For rotor diameter, a tapering off to 120 m ocurrs over the next 20 years.[4] For electricity price, a power law trend is used based on historical data for Europe. The assumption regarding an exogenous electricity price in particular does likely not hold in the case where aggressive policies are used since the expected contribution of wind energy to overall electricity generation would be substantial. In that case, the electricity price could not be assumed to be independent of wind energy development. Nevertheless, the hypothetical example shows some interesting implications of current aggressive policies. Extending the scenario out to the year 2030 (and holding policy variables constant) yields some interesting results.

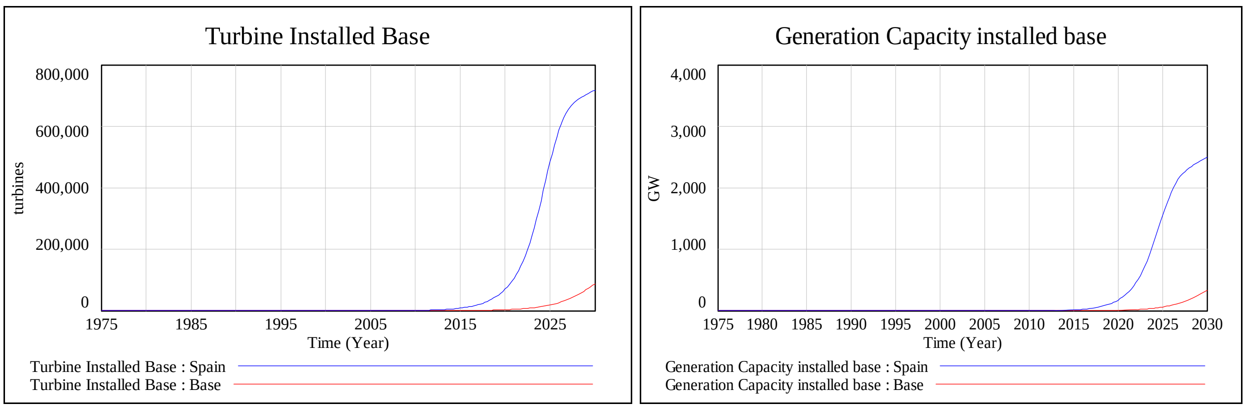

Figure 13: Turbine Installations for Spain and Base Case through Year 2030

The base case leads to strong wind development eventually but the increase in capacity for the case with aggressive policy such as pursued by Spain today leads to capacity levels that would cover nearly 100% of Spain's annual electricity generation needs. The main limitation in the case of the strong policy levers are the effects of population resistance as wind development begins to cover an undesirable portion of available land. While the scenario ignores some important dynamics as mentioned previously, it is interesting to understand the implications for growth of the aggressive policy measures implemented by Spain and many other countries today. High growth rates will quickly lead to various other effects on system integration and overall electricity economics.

Finally, the influence of inconsistent policy is inspected through the application of a series of policies that are enacted and then reversed. This is to mimic the effects of national policies such as seen in Denmark, Germany or the US which provide aggressive support for wind but when the high growth rates lead to unfavorable operational and economic impacts for the overall electricity system, such policies are reversed. Two additional cases are involved in the below figures. The first is the Spanish case without the investment subsidy but with the feed-in tariff

[4] 120 m or roughly 5 MW is seen as a technical limit for wind turbines onshore due to limitations in transportation and installation of larger machines; with endogenous technical innovation, this assumption could be challenged.

still applied through 2030. The last case mimics the situation in the US in the 1980s where a policy was applied over a period of 5 years and then removed and the cycle is repeated again 20 years later. The increasing electricity prices mean that the subsequent "shocks" to the economics of wind energy development are less critical, but there is still an impact on the development trend and in particular on the turbine industry installation capacity.

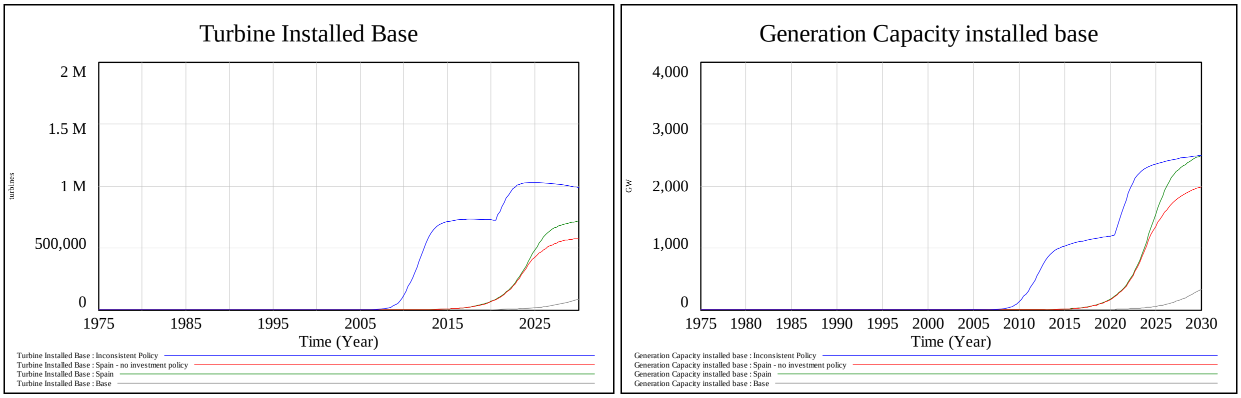

Figure 14: Turbine Installations and Capacity under various policy scenarios

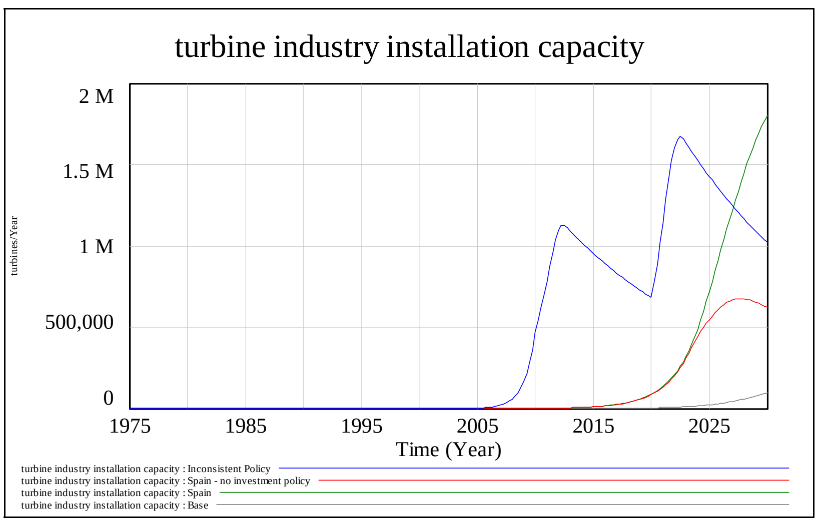

Figure 15: Turbine industry installation capacity as a function of policy scenarios

As can be seen in the above figure, the turbine industry installation capacity overall is much more volatile in the cyclic policy scenario. Such boom and bust conditions are even more accentuated in actual cases since the dynamics of firm financial performance have not been included in the model. Many firms with idle capacity would likely long go bankrupt before capacity ever reached a retirement age under this scenario. Still, even with this simplistic representation, the boom and bust cycles industry cycles begin to emerge. For the same overall amount of applied subsidies, less overall installations result due to the effects of incentive cycling on industry capacity. Regardless, aggressive cyclic capacity still leads to large scale growth in the long term where other dynamics may still begin to appear.

Discussion and Conclusions

Wind energy development has taken many countries and states by storm over the last 10 to 20 years. Policies to pursue wind energy development in many states have been aggressive and have lead to considerable growth rates in both the actual number of installed turbines and wind-based electricity generation. The above model developed for wind energy diffusion has sought to capture some of the simple dynamics involved with wind energy development including resource / land use, industry capacity growth, and public resistance. Under case-based input conditions, the model captures much of the behavior in wind energy development for a number of states especially those cases where wind energy development has occurred more recently. Having established a decent representation of actual historical trends, a generic case is established using input data reflective of the Spanish case. The model is then run for an additional 20 years out to 2030 under two different scenarios: with the current policy conditions for Spain kept active and a base case that eliminates all policy incentive programs. The development under the base case is much lower than for the Spanish case as would be expected. Interestingly, the development for the Spanish case is unrealistically large and is indicative of just how aggressive such policy measures are. The unrealistic growth rates for the model run to 2030 highlight the important missing dynamics of the model. In particular, the dynamic relationships between wind energy development and system operation and economics were left out. In order to fully understand how policy measures would likely affect wind energy development going forward, these dynamics need to be added to the model and this will likely be the future direction for the current work.

Finally, the boom and bust behavior for industry capacity development was illustrated through the implementation of an inconsistent policy that was applied early in the 1980's and then again after the year 2000. While the overall trends for wind energy development in terms of installed base and capacity for the year 2030 were essentially unchanged, the industry itself experienced a much higher level of volatility. Such volatility as seen in the model is likely even lower than would be expected in reality because the capacity loss rate in the model is currently only affected by the age of industry capacity rather than the current financial performance. Future work will also seek to develop a more accurate representation of the industry capacity growth dynamics in order to better understand the impacts of different policy scenarios. This work has showed that there is substantial complexity involved in understanding the development of wind energy. Policies are being enacted that are causing aggressive growth for wind energy worldwide. The long term repercussions of these policies for the industry and for the electricity system overall are not well understood. A simple system dynamic model of diffusion for wind energy that involves public resistance, industry capacity and resource use can provide some understanding of the implications of existing policy. However, in so doing, the model exposes the very complexity that makes understanding the long term policy implications counterintuitive and stresses the need for development of a much more detailed model that would capture the additional dynamics necessary and provide the necessary insight.

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Appendix A: Model Formulation and Equations

The main model structure includes feedback relationships that represent the above discussed dynamics along with a co-flow and development structure for the intrinsic relationships of the model variables and the different phases of development respectively. The main development phases identified for the model include permitting, construction, operation and decommissioning. Every project must go through this process and there is an associated delay for moving from one development phase to the next. In addition, the co-flow structure explicitly links the number of turbines, installed capacity, capacity factor and land use for each phase of the development chain. The series of diagrams below show each co-flow structure as well as the important economic and turbine industry capacity model processes.

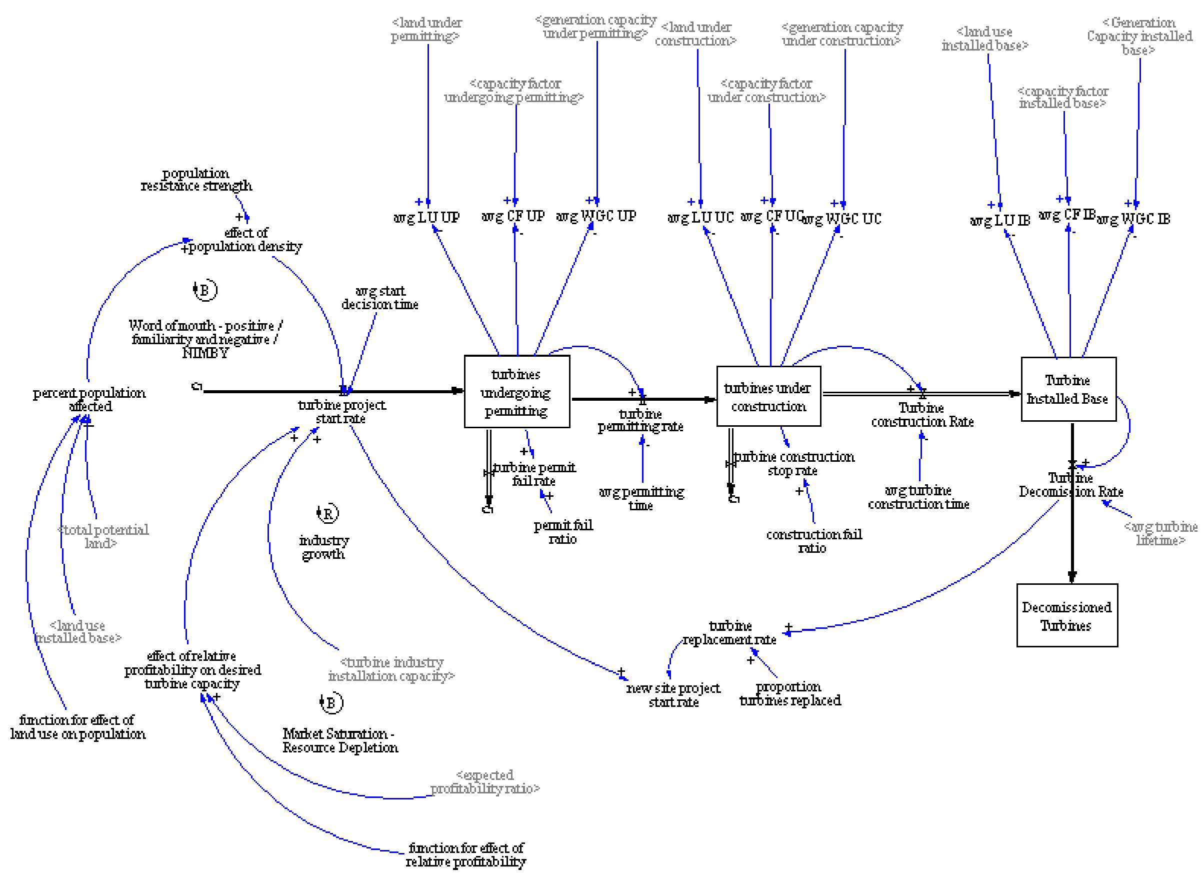

Figure 16: Turbine Installation Co-Flow and Main Dynamic Relationships

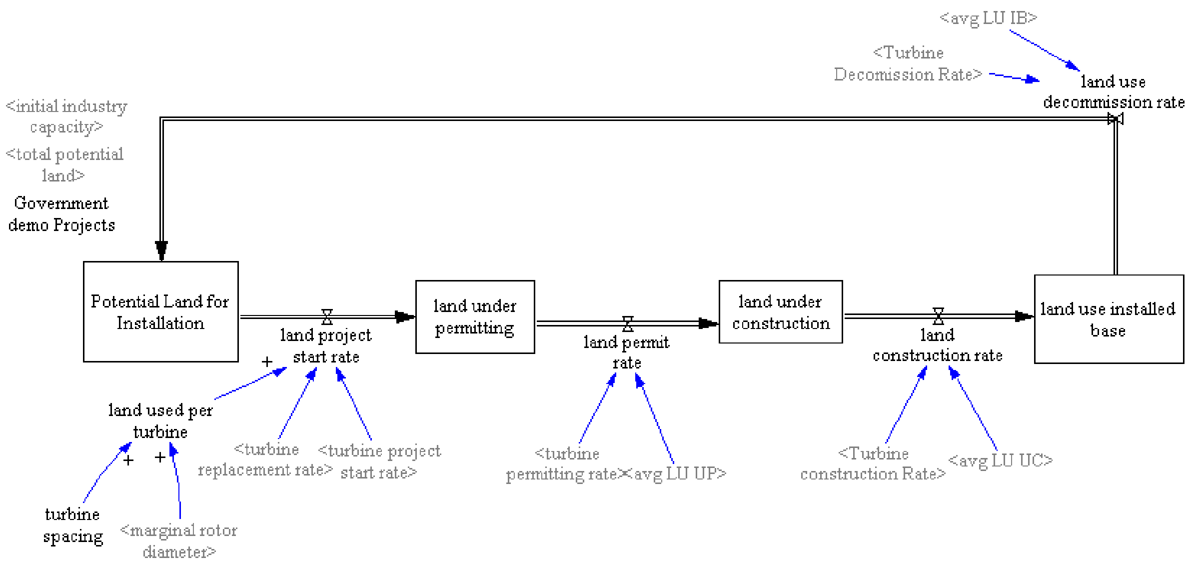

Figure 17: Land Use Co-Flow

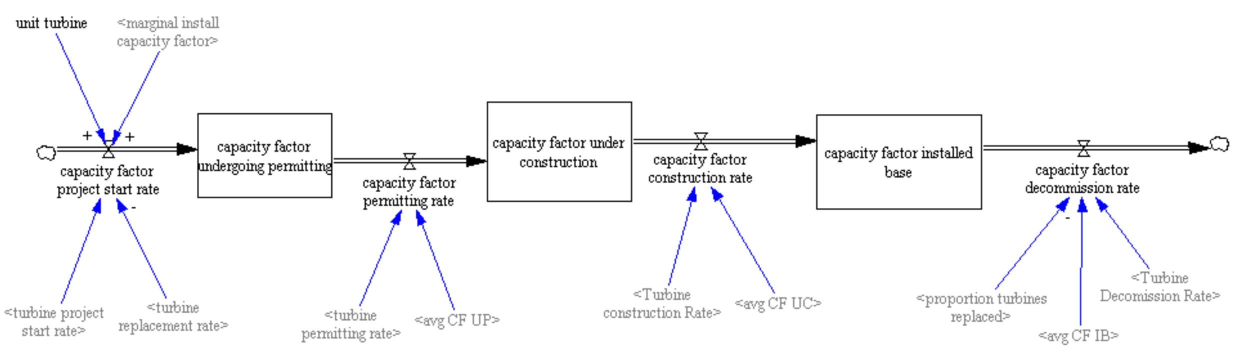

Figure 18: Capacity Factor Co-Flow

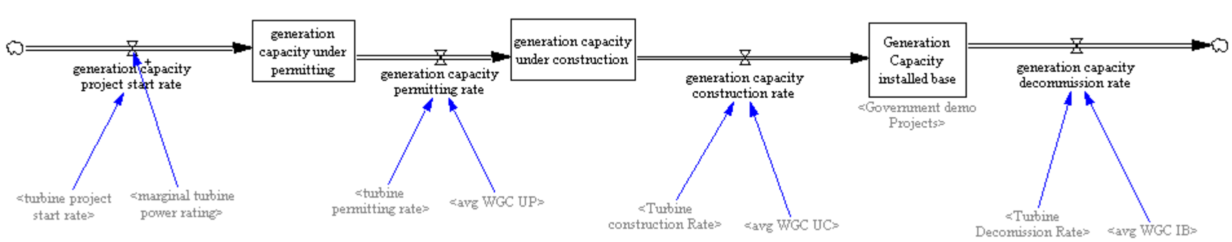

Figure 19: Generation Capacity Co-Flow

The main variable for developing the dynamic relationship is the individual turbine. Associated with each turbine is a capacity factor, rated capacity (or generation capacity), and a physical footprint (or land use). The relationship between these four co-flows is as follows:

Capacity Factor

Capacity Factor for a new project = Marginal Capacity Factor available

Marginal Capacity Factor = f lookup (land under use / total potential land available)[5]

Installed Capacity

Rated Capacity for a new project = f lookup (Rotor Diameter)

Rated capacity is a function that depends on rotor diameter through the below relationship.

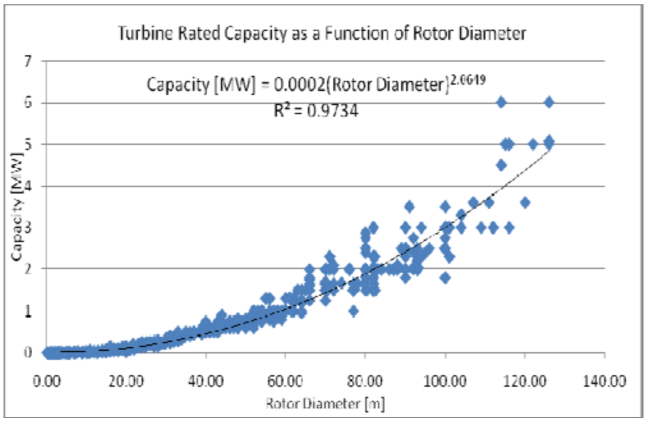

Figure 20: Rated Capacity as a function of Rotor Diameter (the Wind Power Net 2009)

Rotor Diameter = f lookup (time), for exogenous technology evolution

Rotor diameter is exogenous and changes over time.

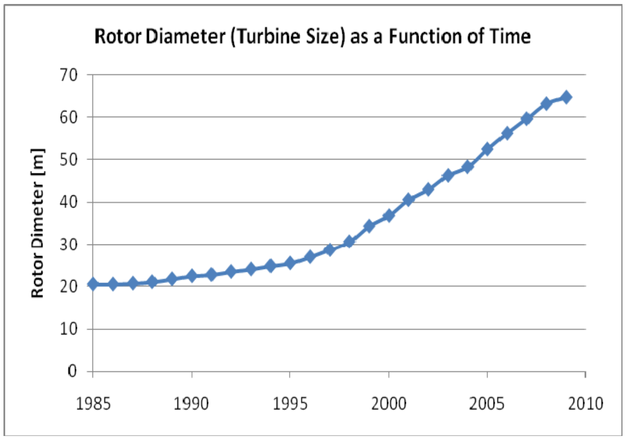

Figure 21: Evolution of Rotor Diameter over Time (the Wind Power Net 2009)

[5] Depends on individual state (see case section for details)

Land Use

Land Use for a new project = Turbine Spacing * (Rotor Diameter ^ 2)

Turbine Spacing = industry recommended constant of 3 x 10

The subsequent co-flows are related by the average value of each co-flow variable in each development stage as shown in the top section of the turbine installation co-flow. Time to move through each successive phase is governed by a series of constants representing typically delays for industry permitting and permitting processes and the average lifetime for a turbine. Finally the central dynamics govern the initial project start rate and include market saturation, industry growth and social processes for the public. The project start rate is governed by the following dynamics:

Turbine Project Start Rate = Turbine Industry Installation Capacity * Effect of Relative Profitability * Effect of Population Density

Effect of Relative Profitability = f lookup (Expected Relative Profitability)

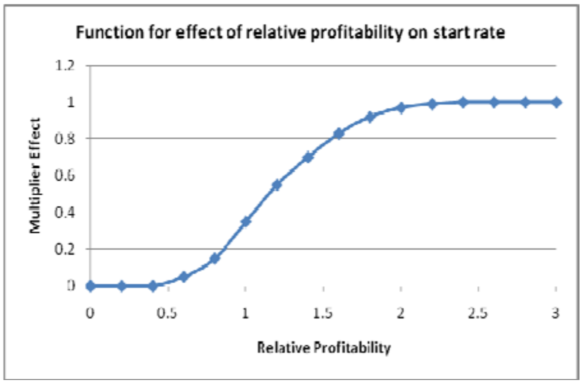

Figure 22: Lookup Function Effect of Relative Profitability

Effect of population density = population resistance strength * f lookup (land use / potential land)

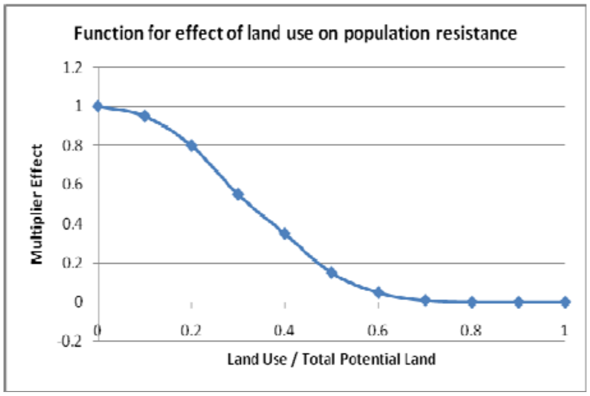

Figure 23: Lookup function effect of Land Use on Population Resistance

The dynamics of relative profitability and industry capacity will be discussed next. "Turbine Industry Installation Capacity" is affected by the expected profitability of new turbine projects with a delay for time to adjust capacity and a loss rate governed by the average capacity lifetime.

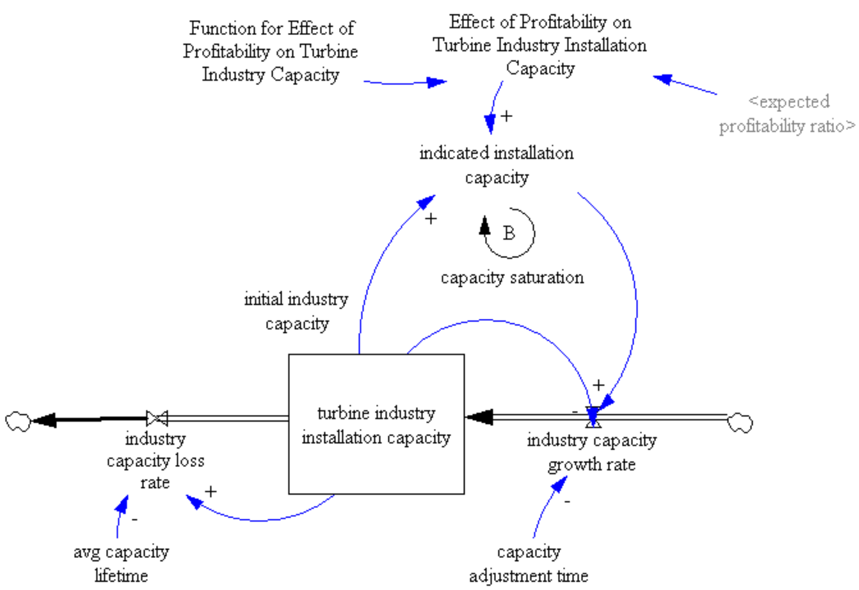

Figure 24: Industry Growth Dynamic Model

The effect of profitability on indicated capacity is governed by a lookup function. Industry capacity adjusted to the indicated capacity by a first order delay for capacity adjustment. Installation capacity has a lifetime after which it is retired.

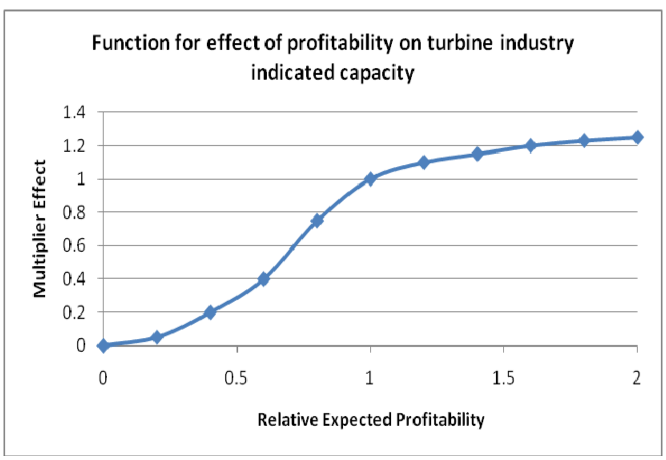

Figure 25: Industry Capacity Lookup Function Based on Relative Profitability

The relative profitability is governed by a series of relationships that relate the marginal turbine rotor diameter and capacity to estimated project energy production, revenues and costs.

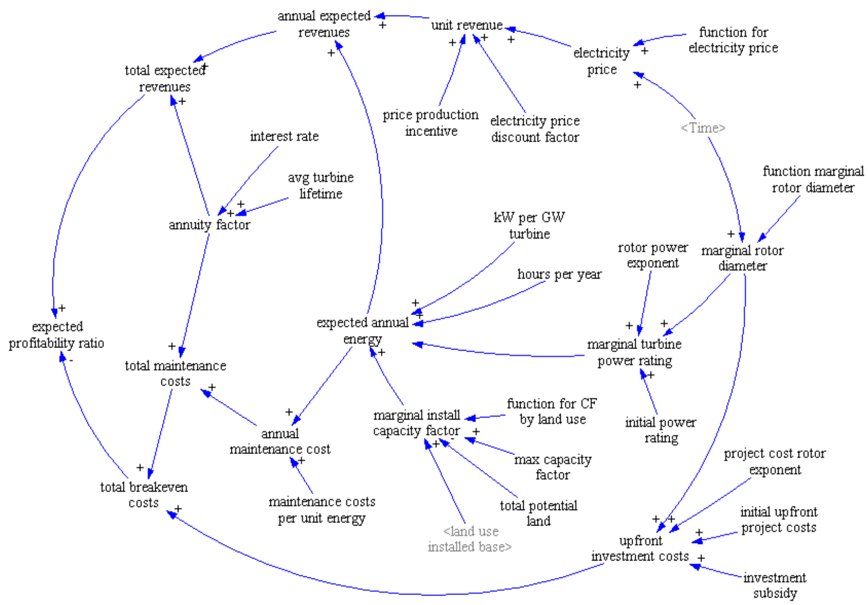

Figure 26: Economic Parameters and Relationships

The project costs and revenues are determined as follows:

Expected Profitability Ratio = Total Expected Revenues / Total Breakeven Costs

Total Breakeven Costs = Total Maintenance Costs + Upfront Investments

Total Maintenance Costs = Annual Maintenance Costs * Annuity Factor

Total Expected Revenues = Annual Expected Revenues * Annuity Factor

Annuity Factor = [1- (1/ (1 + interest rate) ^ project lifetime)]/interest rate[6]

Upfront Investment Costs = (1- Investment Incentive) * [Initial Costs * (Rotor Diameter) ^ Cost Exponent][7]

Annual Maintenance Costs = Maintenance Costs per Unit Energy * Expected Annual Energy[8]

Annual Expected Revenues = Unit Revenue * Expected Annual Energy

Unit Revenue = Electricity Price * Discount Factor[9] + Price Production Incentive

Expected Annual Energy = Marginal Install Capacity Factor * Marginal Turbine Power Rating * Annual Hrs

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[6] Interest rate assumed to be a generic 0.08 but can be adjusted for sensitivity testing.
[7] Rotor diameter = 2 * blade length; turbine blades are ~10% of overall project cost, diameter ~ 6.7% overall project costs; using standard turbine costs models (Fingersh 2006) the estimated upfront project costs based on turbine diameter can be obtained
[8] Maintenance costs per unit energy obtained from generic turbine cost model (Fingersh 2006)
[9] Discount factor is used to set proportion of electricity price to avoided cost for utilities which is the standard measure for how wind energy production should be compensated and is used in setting power purchase agreements for projects (Gipe 1995, IEA 1997-1). This factor can be incentivized such as with a feed-in tariff.

The different policies come into play predominantly on the economics side through different incentives and pricing regulation. The main variables affected by policy are a price production incentive (such as the use PTC – production tax credit), investment subsidies (such as the ITC – investment tax credit), the discount factor (which can be regulated such as in the case of a Feed-In Tariff), or the Interest Rate (which can be affected by Low-Interest Loan Programs). Putting together all of these functional relationships results in a full model that can be used to explore the dynamics of interest. Before using the model for general analysis, a series of cases were used to calibrate and test the model.

Appendix B: Simulation and Actual Results for Remaining Cases

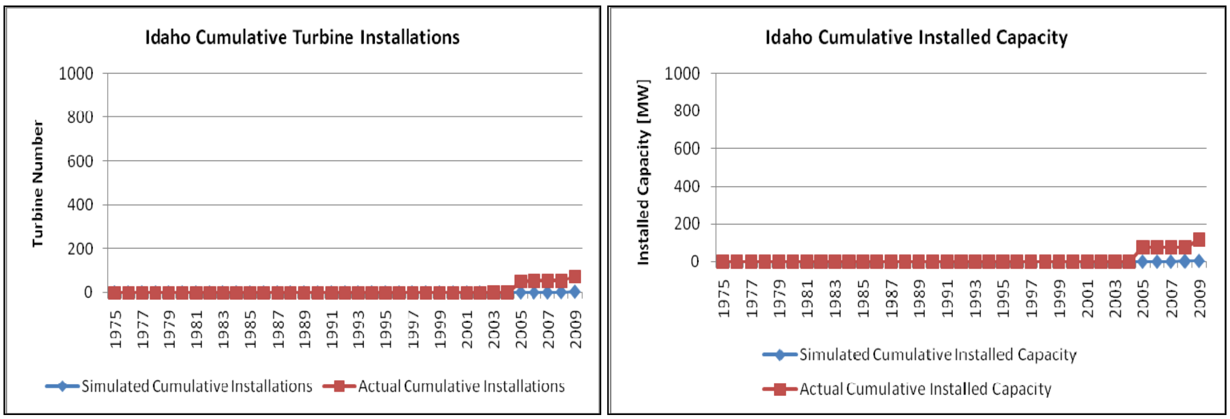

Figure 27: Idaho Turbine Installations and Capacity - Simulated and Actual

With no RPS or advanced incentive programs, cheap electricity and low wind resources, wind energy development in Idaho has been limited.

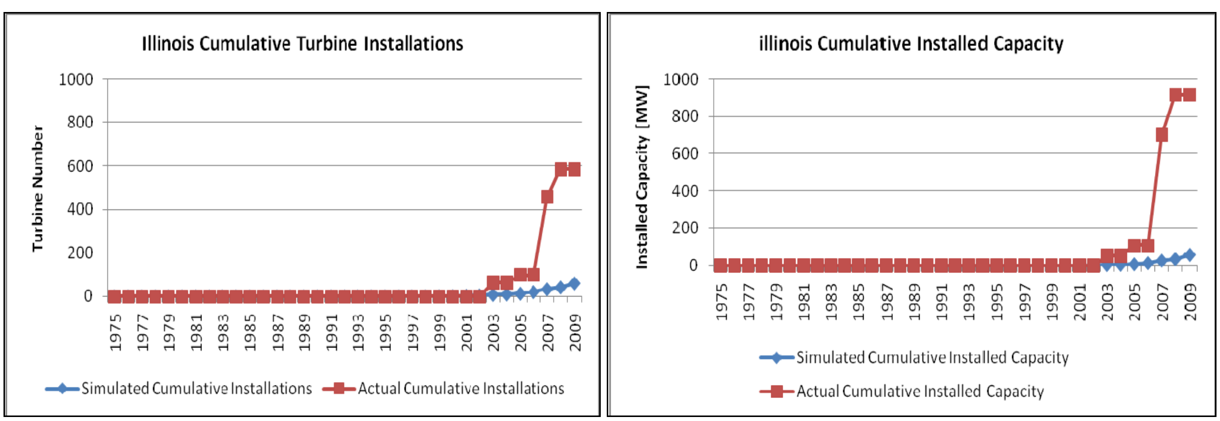

Figure 28: Illinois - Turbine Installations Simulated and Actual

The development in Illinois has been much higher than the model would indicated based on there limited incentive program to date which indicates that other dynamics may be important that have not been fully captured by the model.

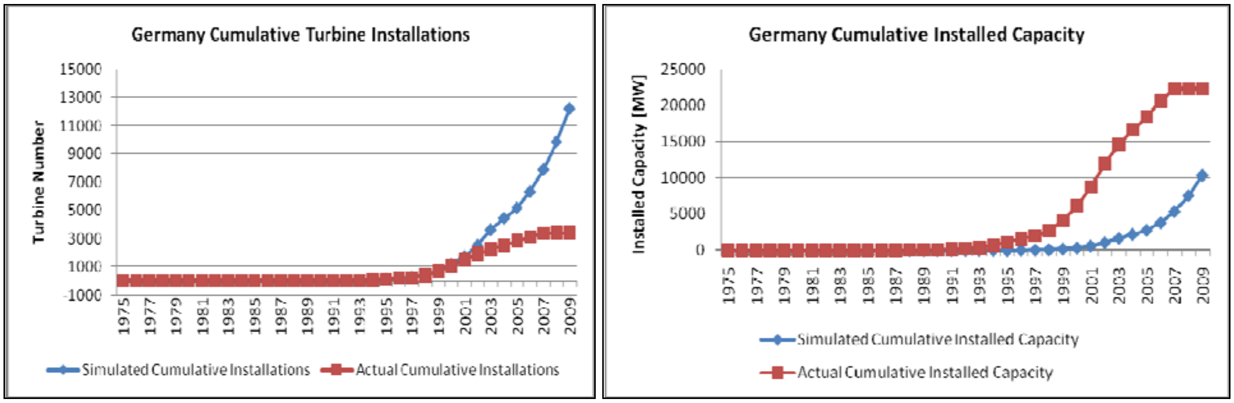

Figure 29: Germany - Turbine Installations Simulated and Actual

German development has been higher in capacity terms and lower in turbine number than simulations suggest implying the exogenous technology trend may be inappropriate for this case.

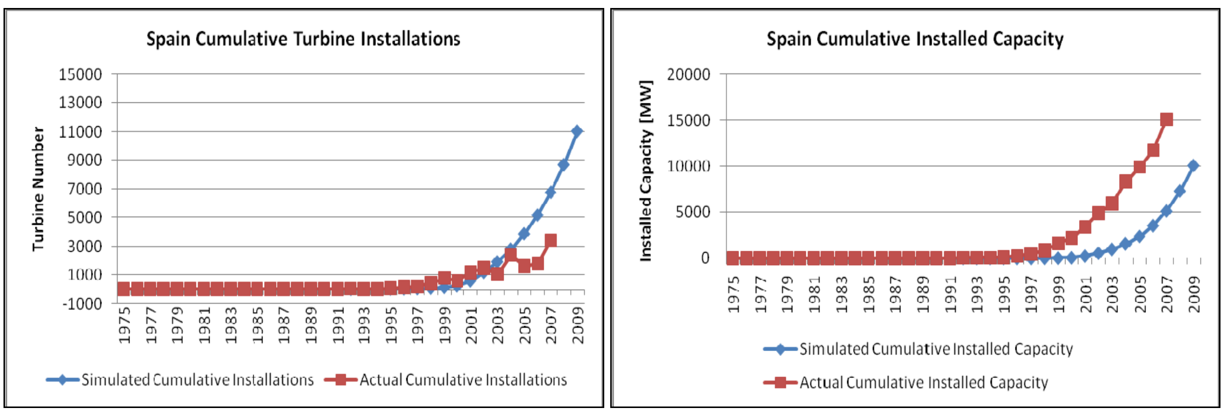

Figure 30: Spain - Turbine Installations Simulated and Actual

Spanish development has been higher in generation and lower in turbine trends indicating again that the exogenous trend for marginal rotor diameter increase with size may not be appropriate. However, there also may be some limitations of the data base source information since individual case data involves a large number of data points from all over the globe. Thus, the similarity in the trend of development is an indication that the model does a decent job of representing the relevant dynamics.