

Abstract

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 poster 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. The model captures the basic dynamics for each of the individual cases but there are limitations especially with respect to the fact that integration issues associated with large wind penetration into the electric grid are ignored. This is systematic within prior system dynamics models for long term electricity generation planning and also in many economics-based models. The model developed shows how such a framework that ignores integration issues will overestimate either the magnitude or the costs of wind energy integration.

Follow up work highlighted here considers the various sources of integration issues associated with wind energy and looks at a broad cross-section of wind integration studies to look at generalized impacts of large-scale wind energy integration on both economics and reserve capacity requirements. Subsequent work is then proposed that will integrate the case-calibrated system dynamics modeling for long term planning with information on economic and operational impact of large-scale wind integration for improved system planning and policy analysis.

System Dynamics for Wind Energy

System dynamics is a model that addresses technical, social and economic relationships for a truly holistic system analysis. In the case of wind energy, a long history of capacity expansion models have been developed for generation and transmission planning on the time-scale of a few years to a few decades. However, such optimization based models deal only with optimization of economics based on a pre-specified set of technical constraints. Potential for incorporating dynamics such as technical learning curves or social constraints are limited. System dynamics as a method has been applied previously to many electricity planning scenarios, perhaps most notably for the integrated resource plan (IRP) of the Bonneville Power Administration (BPA). The core of a system dynamics method is the recognition of the various feedback relationships in a socio-technical system. For instance, with respect to wind energy, one obvious example is resource depletion whereby the best sites are taken up and subsequently the remaining sites are less profitable which may then limit or “balance” the inertia for adding additional wind installations in a system. Such a simple “balancing” feedback relationship is illustrated in the diagram below where the positive sign indicates a direct relationship while the negative sign indicates an inverse relationship.

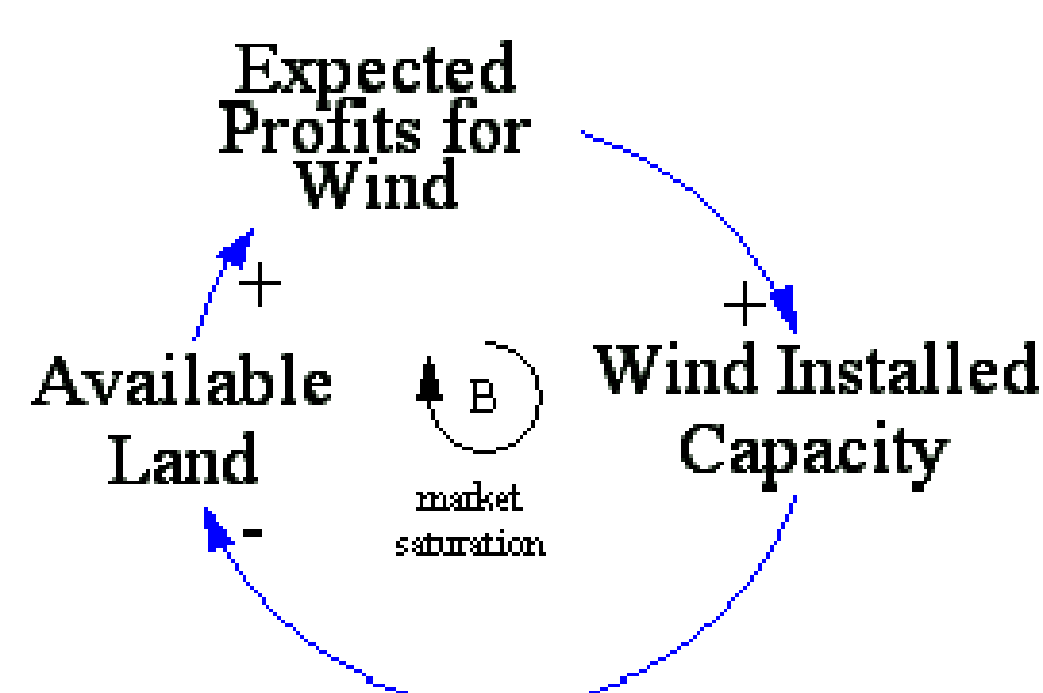


Figure 1: Example of a resource depletion balancing feedback relationship for wind energy

Another easy to identify example is a learning curve whereby the more installations of wind turbines that are achieved by a company and/or industry, the better the technology gets and the lower the per unit costs. This is a “reinforcing” feedback since the more you produce, the lower the cost, which promotes further sales of the technology. There are many such important feedback relationships in the wind industry. The below diagram highlights some of the most important social, economic and technical feedbacks of a wind energy adoption/diffusion system.

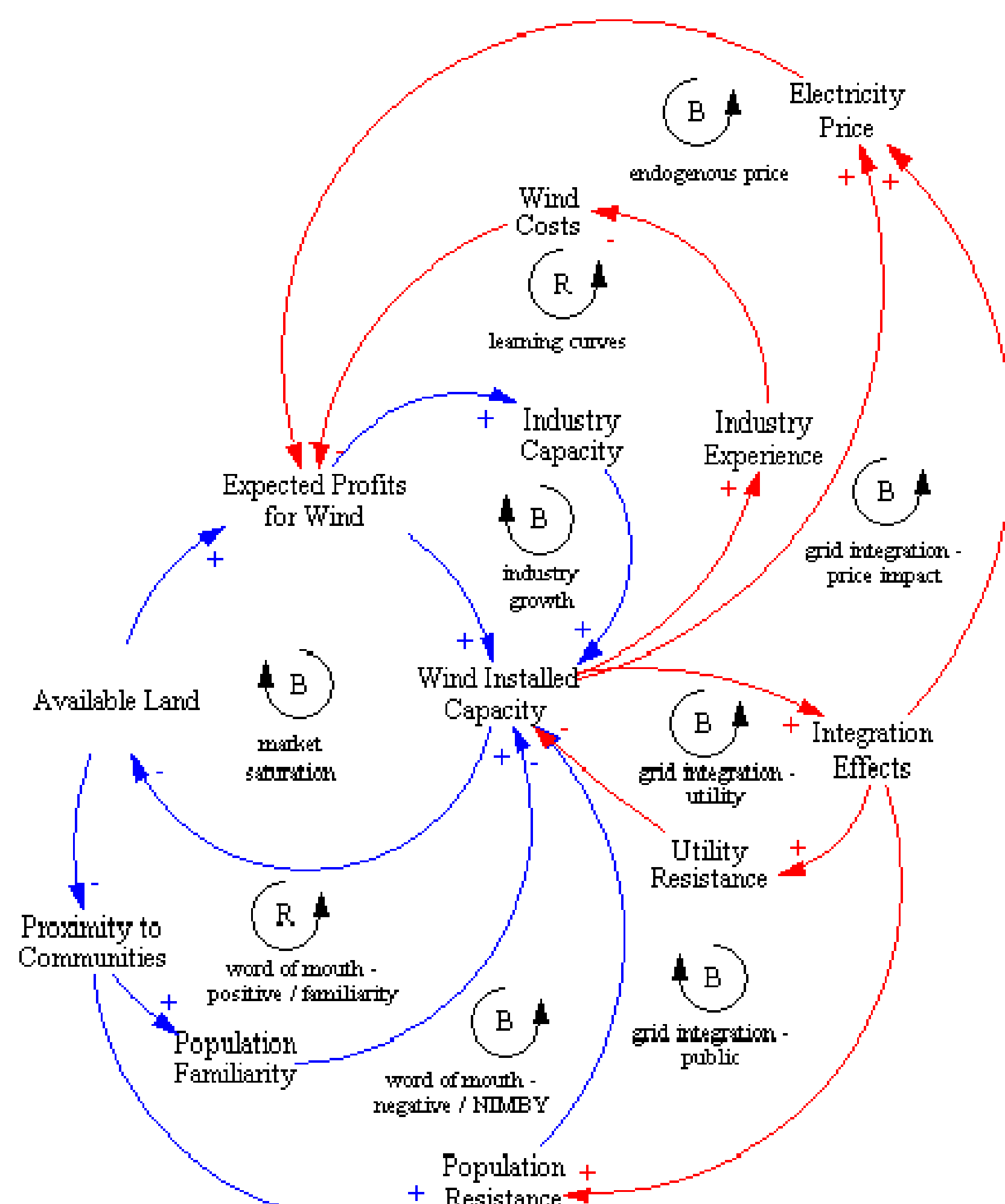


Figure 2: Full set of important feedback relationships for the wind energy sector

Case Level Model and Analysis

In terms of analysis, it is possible to look at the global wind industry, or at particular regions or states. For the purpose of this study, a state (or European national) level was chosen for analysis specifically because incentives for wind energy and regulatory frameworks are often significant at this level. There are some 25 nations/states that have over 1000 MW of installed wind capacity (excluding US and Canadian national borders). Different states use different policy mechanisms to promote wind development which can influence the overall development process. Below is a pie chart that shows the different policies invoked by nations/states supporting wind energy development.

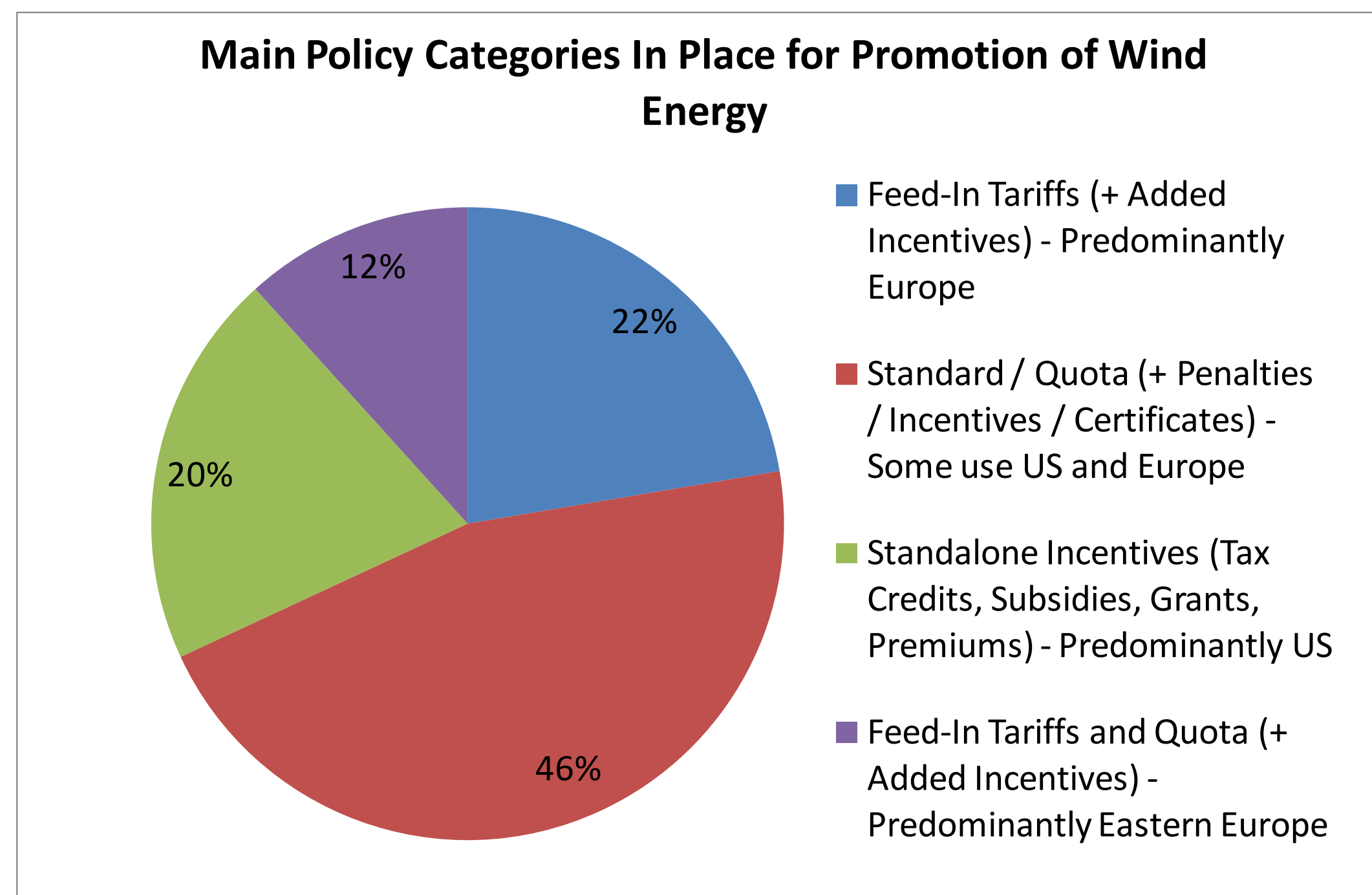


Figure 3: Policy measures used to support wind energy development

For a case level model, certain aspects of the system had to be considered exogenous. The main assumptions of the model are that the red loops of figure 2 are negligible at the case-level. As we will see, this assumption does not hold for certain relationships such as that having to do with large-scale wind energy generation. The main assumptions of the case model are:

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

Based on the above set of assumptions, a large database of information was compiled to set the initial conditions for the model for a set of cases including:

1. Feed-in Tariffs: Germany, Spain, Portugal, Denmark
2. Standard/Quotas: Colorado, Illinois
3. Incentives: California, Idaho

Below are some of the results for these different cases.

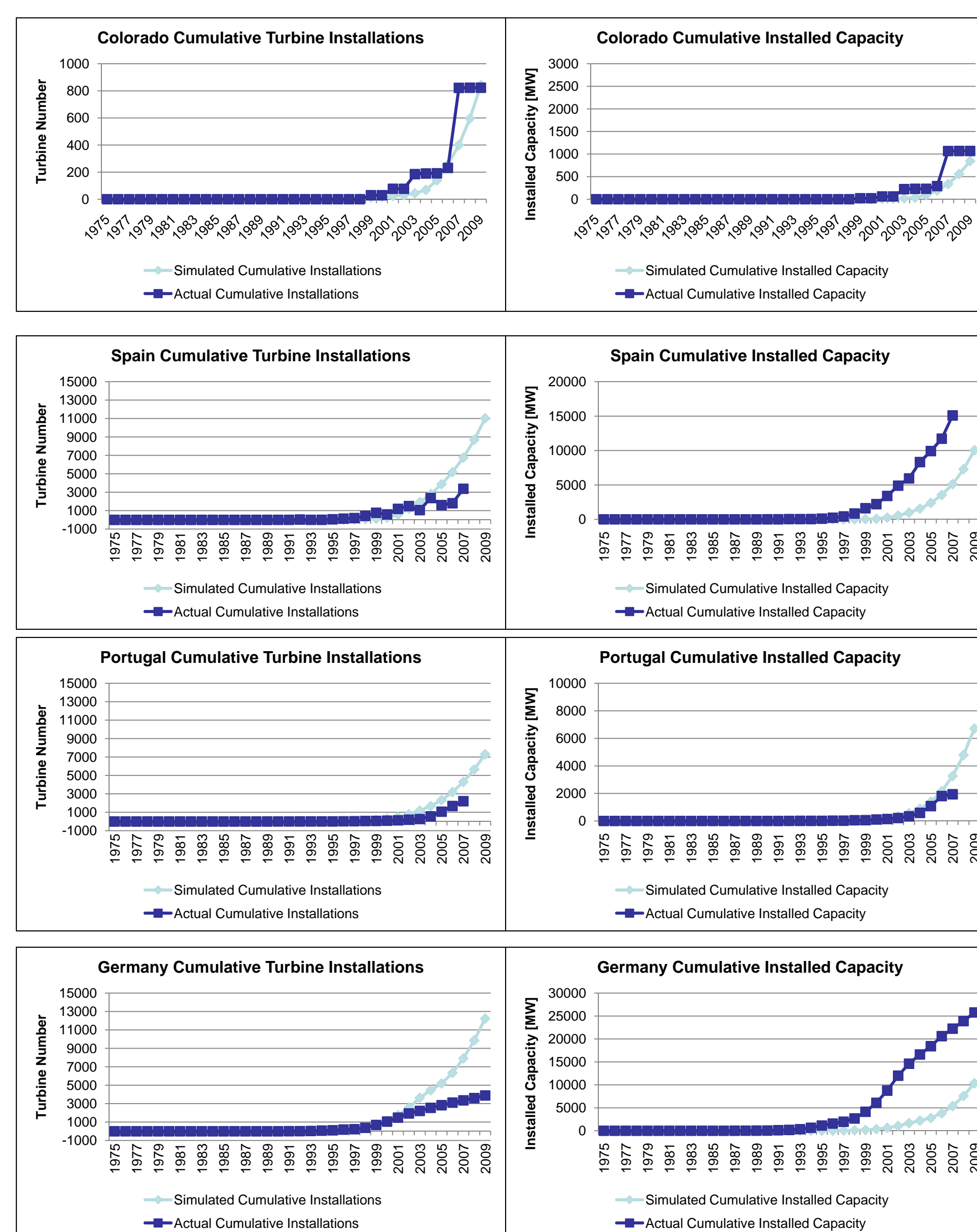


Figure 4: Model simulation results and actual data by case

There is a better fit between the model and actual data in certain cases while the overall trend is captured. For more detail on the model formulation and results, the references specified to the right provides a discussion of each case and results. One especially interesting result from the above is the over-prediction of development in the German case which may be indicative of integration issues surfacing with larger wind penetration levels.

Integrating Wind into the Grid

There are obvious shortcomings to a long-term planning model that does not change its assumptions regarding the operations and economics of wind energy at levels beyond 5-10% wind energy penetration by overall electricity consumption. However, models historically have not been designed to accommodate for such high levels of wind energy. Some 40 studies have been developed, predominantly in Europe and North America, which look at the impacts of large-scale wind energy on grid operations and economics. However, such studies will vary by system and there are many different sources of variation both in the methods used and the types of systems characteristics as shown in the below table:

Wind	Generation & Transmission	Demand	Regulation and Market Structure
Resource (capacity and variability)	Generation Asset Mix and Technical Characteristics	Demand Profile	Planning Time-Scales for System Commitment
Number and size of turbines	Reserves and Storage Assets	Demand-Side Technology	Interconnection Characteristics Between Balancing Authorities
Turbine Technology	Transmission Technology and Capacity		Information Transparency and Sharing
Geographic Dispersion of Turbines	Distributed Generation in System		Grid Codes and Standards

Table 1: Factors affecting wind energy integration into the grid

Despite these differences, there are enough studies to date where we can begin making some generalizations across cases. For instances, we can look at the different levels of wind energy studied across cases and see a general trend beginning to emerge in terms of anticipated impacts:

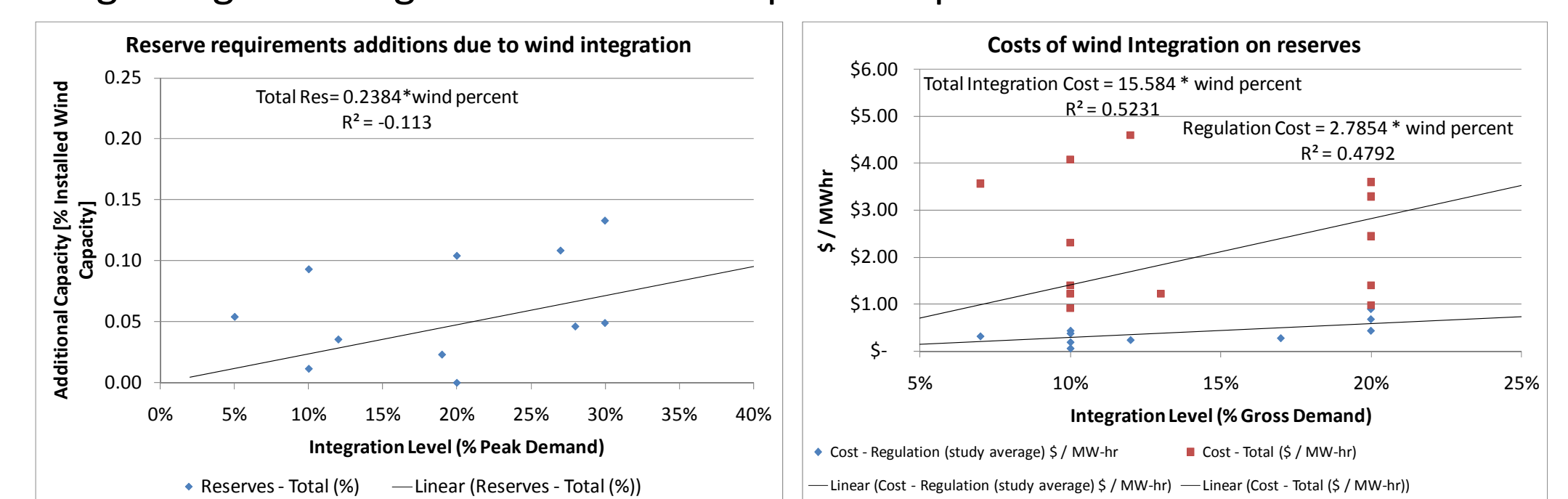


Figure 5: Results across different large-scale wind integration studies

For truly generalizable results, more detail has to be paid to the system factors and methodological differences between the studies. For more on this analysis, see the second reference below.

Discussion and Next Steps

There is a wealth of historical information today that can be used to look at the development of the wind energy industry. A system dynamics model of wind energy diffusion has been developed to capture the different dynamic relationships in the overall wind energy sector. These dynamics include technical characteristics such as resource depletion and economic concerns such as technology learning curves but also social dynamics related to NIMBYism and population density issues. The model was set-up to handle initial conditions for a variety of cases using European national and North American state/province levels for analysis. As can be seen in the results to the left, there was a good overall fit of the simulation results to the actual data across a number of cases including a range of policy-support conditions.

However, as we move to the next stage of development where wind becomes an even more significant component of our electricity generation portfolio, certain dynamics will begin to surface. In particular, those dynamics related to the operational and economic impacts of large-scale wind energy on different grid systems will become important and can not be ignored in long term planning for both transmission and generation capacity. A large body of work has begun completed that looks at wind integration issues on a case by case basis for very specific sets of conditions related to the levels of wind energy generation as well as the overall system characteristics. General analysis across these cases and in this field is necessary in order to be able to capture such integration dynamics in capacity and transmission planning models. Future work will look at extending the model discussed here to the case where wind energy integration issues can no longer be ignored. Since several states across the US and the world are now beginning to cope with such realities, a model that does not address these characteristics will not be of use for long-term planning of wind energy and grid transmission and capacity.

References

[1] Dykes, K. and Sterman, J. “Boom and Bust Cycles in Wind Energy Diffusion Due to Inconsistency and Short-term Bias in National Energy Policies,” *ICSD 2010 Conference Proceedings*, July 25-30, 2010.

[2] Dykes, K. “Aggregate Effects of System Integration for Analysis of Wind Energy Diffusion,” *IEEE Energy 2010 Conference Proceedings*, Sept. 27-28, 2010.

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