Hot Air? When Government Support for Intermittent Renewable Technologies can Increase Emissions

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November 21, 2008

Abstract

This paper analyzes the effects of an intermittent technology on long-run incentives for investment in non-renewable electricity generation technologies. I find conditions under which supporting an intermittent technology may in fact increase carbon emissions. The variability of load usually determines the long run mix of generating technologies in a competitive electricity market. When there is a significant amount of intermittent production the mix of other generating technologies is determined by the variability of net load (load net of intermittent output). Net load may be more variable than load itself if the intermittent output is not too positively correlated with load. This increase in variability results in a substitution away from baseload generating technologies towards peaking and intermediate technologies. If peaking and intermediate technologies are more carbon intensive than non-renewable "baseload" technologies, this substitution can more than offset the emission benefits derived from the output of the renewable technology.

1 Introduction

This paper analyzes the effects of support for intermittent technologies on long-run incentives for investment in non-intermittent electricity generation technologies. Currently there are a broad range of policies supporting a number of intermittent renewable technologies (e.g. wind, solar) by governments to deal with the prospect

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of climate change. I analyze how and when support for a clean intermittent technology is likely to be effective at reducing greenhouse gas (GHG) emissions from electricity generation. For instance proponents of wind generation argue that they promote investment in a clean source of electricity and therefore reduce greenhouse gas emissions. I derive the conditions under which this may or may not be true. The countervailing force, which may increase emissions, acts through a change in the efficient (least cost) mix of non-renewable generation when wind provides a fraction of electricity. If this mix involves more GHG intensive generating technologies then this will act to offset the emission gains due to the output from wind.

Absent government intervention, the long run mix of technologies in deregulated electricity markets will reflect the variability of demand. That is if demand is highly variable then the mix of generation will consist of a greater fraction of peaking and intermediate generation than it will if demand is less variable. If an intermittent technology is introduced, and one assumes it operates whenever the power source is available, then investment in technologies other than the intermittent technology will reflect the shape of electricity demand minus intermittent generation. Both electricity demand and intermittent generation exhibit variability over time. When the intermittent generation is not too positively correlated with electricity demand the difference between the two will exhibit a greater variance than either one individually. This increase in variability will be reflected in the pattern of investment and will lead to a greater amount of peaking and intermediate investment relative to baseload investment. In the long run, the entire mix of generating technologies which supply electricity will be affected. The flow on effect to carbon emissions of support for the intermittent technology through the change in the mix of investment may be positive or negative.

The contribution of this paper is to give a general characterization of the long run impact of government support for intermittent technologies. There is work that has aimed to do this empirically in some geographic areas. DeCarolis and Keith (2006) look at the economics of wind power for reducing GHG emissions by employing a greenfield optimization model that determines the optimal mix of wind, gas, turbine, storage and transmission capacities in a hypothetical electricity system under a carbon tax, using data from 5 sites in the mid west. There are also a number of studies of the effects or likely effects of RPS policies, production subsidies and other policies which promote intermittent technologies such as wind and solar for various jurisdictions on a case by case basis. In contrast to these empirical approaches the approach in this paper is theoretic. Economic theory is particularly relevant in this context because it allows one to understand and potentially estimate the effects of policies with which there is little or no historic data. In the case of the long-run impact of significant intermittent generation there is currently insufficient investment in intermittent technology over a time-frame which is too short to empirically estimate the effects.

Section 2 introduces a model of a competitive electricity market with long run investment in different generating technologies, Section 3 analyzes the effects on investment from supporting an intermittent technology and the conditions under which it can increase carbon emissions and Section 4 concludes.

2 Model

In this section I introduce a model to analyze the effect on long run incentives for investment in generation in a deregulated electricity market when there is government policy supporting an intermittent technology.

2.1 Demand

I assume that consumers have a perfectly inelastic demand for electricity. This analysis may be extended to include more elastic demand, however the inelastic case gives the most transparent exposition of the mechanism by which government support for intermittent technologies affects investment in other generation. Electricity demand varies across the course of a year. I normalize average demand for electricity to 1 and describe the annual shape of electricity demand by the cdf $F_d(x)$ and associated pdf $f_d(x)$ where x is the ratio of actual demand to average demand. I denote peak demand by $\overline{x}$ where $\overline{x} = \inf\{x | F_d(x) = 1\}$

2.2 Generation technologies

2.2.1 Conventional generation

I assume there is a finite set of conventional investment opportunities denoted by i and characterized by a constant marginal cost of production c_i ($/MWh), per year capital cost K_i ($/MW) and carbon intensity EI_i (tonnes of CO_2 equivalent emissions per MWh). I assume that these technologies are dispatchable (not intermittent) and may produce output less than or equal to their total capacity at any point in time.[1] Also I assume no two technologies have identical marginal and capital costs. Amongst this set of potential investments the least cost technology(s) to build if it is utilized $u\%$ of the time is $H\left(u\right)$ where

$$H\left(u\right) = \arg\min_{i} K_i + uc_i$$

$H^{-1}\left(i\right)$ defines a closed interval $\left[u_l^i, u_h^i\right]$ of rates of utilization over which the technology i is the least cost. I now define the set of least cost technologies as $G^* = \left\{i | i \in H\left(u\right) \text{ for some } u \in \left[0,1\right]\right\}$. For the rest of the paper I will often refer to a generation technology by u whereby the marginal cost, per year capital cost and carbon intensity of a technology u are simply $c_{H(u)}, K_{H(u)}, CI_{H(u)}$. I describe the technology $b = H\left(1\right)$ as a baseload technology ($H^{-1}\left(b\right) = \left[u_l^b, 1\right]$) and the set of technologies $G^*/H\left(1\right)$ as peaking/mid merit technologies.

I also assume that there is a technology $\underline{i}$ for which $K_{\underline{i}} = 0$ and $c_{\underline{i}} > K_{h(1)} + c_{h(1)}$ (this can be thought of as the market price in the event of rationing due to insufficient generating capacity).

2.2.2 Intermittent technology

There is an intermittent technology denoted by w. I assume that relative to the least cost conventional technologies it has a low marginal cost of production $c_w < c_{H(1)}$, relatively high fixed costs K_w so that it would not be invested in absent government support and creates no emissions $EI_w = 0$. Furthermore it is an intermittent technology such that it's output fluctuates over time depending on the availability of it's source of energy. I assume that the cumulative distribution function which describes the profile of availability across the year is $F_w^s\left(a\right)$ (with associated pdf $f_w^s\left(a\right)$) where a is actual wind output. The primitive of the model is the joint distribution of wind output and electricity demand $F_{dw}^s\left(x,a\right), f_{dw}^s\left(x,a\right)$ from which both the distribution of wind and demand may be derived by integrating out the appropriate argument. The superscript s is the percentage of electricity generated by the intermittent technology ($\int_0^\infty \int_0^x f_{dw}^s\left(x,a\right) da dx = s$).[2]

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[1] The analysis does not consider start up costs or ramping rates of different technologies.

[2] In general $f_w^{2s}\left(a\right) \neq f_w^s\left(2a\right)$ because as more electricity is generated by the intermittent technology more geographically disperse locations will be utilised. None of these sites will be perfectly correlated with one another so some of the variation from each site will be offset by the variation of other sites.

2.3 Market design

I assume there is a deregulated electricity market where generators bid their capacity into a spot market and a system operator dispatches generation by balancing supply and demand in the least cost manner based on generator bids and subject to system constraints. I assume the market is competitive such that generators bid all of their capacity into the market at marginal cost and the market clearing price is determined by the marginal cost of the last unit of generation required to balance supply and demand. When there is insufficient capacity to meet demand I assume that demand is rationed and the price is set by the system operator at $\overline{p} \geq c_{\underline{i}}$ so that in the event of rationing there is a price signal to provide incentives for investment in technology $\underline{i}$ even if it is expected to run a very small fraction of the year. Alternatively one could also interpret $\overline{p} = c_{\underline{i}}$ as the market price in the event of rationing.

2.4 Government support for the intermittent technology

I assume the government support for the intermittent technology results in a percentage $s\%$ of electricity coming from that source. Without the government support the assumptions in the model are such that the intermittent technology is not competitive based on its capital and variable costs.

3 Results

I describe the equilibrium level of investment by a decreasing function $Z(u)$. The amount of capacity investment in each technology $i \in G^*$ is then given by $Z\left(u_l^i\right) - Z\left(u_h^i\right)$.

3.1 Investment without government support

In this section I illustrate how the efficient mix of investment in generation is related to the shape of electricity demand.

Lemma 1 *Under perfect competition and free entry the mix of investment* Z^* *is given by:*

$$Z^*(u) = F_d^{s-1}(1-u)$$

Proof. Given a mix of investments Z^* all generators make zero profits and for every technology u it's position in the merit order is such that it is used for exactly $u\%$ of the year.

To see that a technology is always utilized efficiently a simple rearrangement of the above relationship yields $u = 1 - F_d\left(Z^*\left(u\right)\right).$ This says that the percentage of demand greater than the amount of capacity with efficient utilization rates above $u\%$ is exactly $u\%$. Now since $c_{h(u)}$ is decreasing in u and generators bid competitively a generator $u's$ position in the merit order is such that it is utilized $u\%$. Thus the choice of investment technologies is efficient under Z^*.

To see that generators make zero profits note that technology $\underline{i}$ (with zero capital costs $K_{\underline{i}} = 0$) always sets the price when it is utilized under Z^*. Thus the price it receives in the market exactly offsets its variable costs $c_{\underline{i}}$ and it makes zero profits. Now given Z^* the technology immediately ahead of $\underline{i}$ in the merit order $i_{(2)}$ receives inframarginal rents $c_{\underline{i}} - c_{i_{(2)}}$ during all the hours that $\underline{i}$ sets the price which is exactly the percentage of hours below which $\underline{i}$ is a more efficient technology than $i_{(2)}$. Technology $i_{(2)}$ becomes marginal when $u_{(2)}c_{\underline{i}} = K_{i_{(2)}} + u_{(2)}c_{i_{(2)}}$ which is precisely the revenue earned by both technologies in the wholesale market during the top $u_{(2)}\%$ of hours of demand. For all hours while $i_{(2)}$ is marginal it earns zero profits because the price is $c_{i_{(2)}}$. The same argument applies for $i_{(3)}$ and all technologies higher in the merit order such that given Z^* all technologies exactly cover their capital costs during hours in which they are inframarginal. ■

Lemma 1 shows how the mix of investments is closely linked to the shape of demand given by F_d. Thus in the long run changes in the shape of electricity demand will be reflected by the mix of generating technologies in the market.

3.2 Investment with support for wind

I assume that the government policy binds so that the intermittent technology provides $s\%$ of electricity. Therefore investment in conventional technologies provides $(1-s)\%$ of electricity, this is the net load which is simply the original demand less wind output. The mix of "conventional" investment when there is support for wind reflects the shape of the net load. I denote the shape of net load b by $\tilde{F}_n^s\left(b\right), \tilde{f}_n^s\left(b\right)$. Note that net load

$$b = x - a$$

so that

$$\begin{aligned}\tilde{f}_n^s(0) \text{ is a mass point} &= \int_0^\infty \int_x^\infty f_{dw}^s(x,a)\,dadx \text{ for } b=0\\ \tilde{f}_n^s(b) &= \int_0^\infty f_{dw}^s(b+a,a)\,da \text{ for } b>0\end{aligned}$$

and

$$\tilde{F}_n^s(b) = \int_0^b \int_0^\infty f_{dw}^s(y+a,a)\,dady + \int_0^\infty \int_x^\infty f_{dw}^s(x,a)\,dadx$$

Note that at the mass point $b = 0$ wind output is greater than total electricity demand and must be curtailed. The following lemma characterizes the mix of investment when there is government support for an intermittent technology.

Lemma 2 *Under perfect competition and free entry the mix of investment under government support for an intermittent technology $\tilde{Z}^*$ is given by:*

$$\tilde{Z}^*(u) = \tilde{F}_n^{s-1}(1-u)$$

Proof. See the proof of Lemma 1. ■

The new mix of investment in nonrenewables now reflects the residual demand. The impact of the government support on non-renewable investment occurs through its impact on the shape of the renewable demand which in turn stems from the correlation of the intermittent renewable technology with actual demand.

3.3 Effect on baseload vs peaking/intermediate technologies

In this section I show how investment and output in baseload and peaking technologies are affected by the intermittent technology. I show that investment always substitutes away from baseload technologies and similarly that total baseload output will decrease. On the other hand investment in and output from peaking/mid merit technology may increase because some of the substitution away from baseload output and capacity may, in fact, be directed towards the peaking/intermediate technology.

Result 1 *Support for an intermittent technology can only induce investment to substitute away from the baseload technology*

Proof. The total capacity investment in the baseload technology is determined by the cumulative distribution of demand $F_d(x)$ and the utilization rate above which the baseload technology is the most efficient u_b. The efficient level of investment in baseload capacity X_b^{Cap} satisfies

$$F_d\left(X_b^{Cap}\right) = 1 - u_b$$

Similarly investment in the baseload technology under government support for an intermittent technology is determined by the cumulative distribution of the residual demand $F_n^s\left(\tilde{X}_b^{Cap}\right)$ and u_b.

$$F_n^s\left(\tilde{X}_b^{Cap}\right) = 1 - u_b$$

Now the cumulative distribution function of demand F_d first order stochastically dominates the cumulative distribution function of residual demand F_n^s since residual demand is weakly less than actual demand. This immediately implies $\tilde{X}_b^{Cap} \leq X_b^{Cap}$ and so the total capacity of baseload technology will weakly decrease under government support for an intermittent technology. ■

Result 2 *Output from the baseload technology cannot increase under government support for an intermittent technology*

Proof. Output declines as an immediate consequence of F_d FOSD $\tilde{F}_n^s$. ■

These results show that neither output not capacity substitute towards a baseload technology when government support for an intermittent technology is introduced. The same is not necessarily true for peaking technologies as the following proposition demonstrates.

Result 3 *The capacity and output of/from peaking/intermediate technologies can increase under government support for an intermittent technology*

Proof. The total capacity of peaking technologies increases when $\tilde{X}_b^{Cap} < X_b^{Cap}$ and the output of wind capacity at peak demand is sufficiently small such that $F_d^{-1}(1) - F_n^{s\ -1}(1) < X_b^{Cap} - \tilde{X}_b^{Cap}$. Output from peaking technologies increase when the renewable output is sufficiently negatively correlated such that $\int_0^{u_b} u \frac{1}{f_d\left(F_d^{-1}(1-u)\right)} du < \int_0^{u_b} u \frac{1}{f_n^s\left(F_n^{s-1}(1-u)\right)} du$. ■

This can be the case when there is significant wind output during the lowest $1 - u_b$ percentile hours of electricity demand. Figure 1 illustrates this situation where a significant amount of output is occurring during the lowest hours of demand.

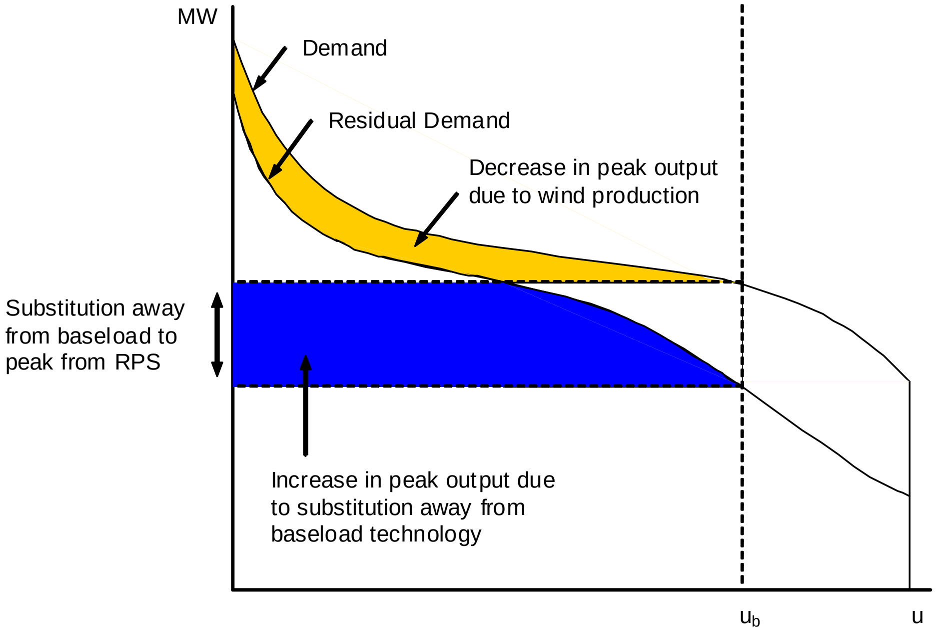

Figure 1: Substitution to peaking and mid-merit

In effect a combination of the intermittent technology, during offpeak hours and peaking/mid merit technology, peak hours, is replacing baseload output. This may have adverse effects for greenhouse gas emissions if the baseload plant that would have been invested in is cleaner than the combination of peaking/mid merit and intermittent technology.

3.4 Carbon emissions

In this section I derive the conditions under which government support for an intermittent technology will increase carbon emissions. It is informative to discuss carbon emissions in terms of the relative carbon intensities of the mix of non-renewable technologies $\lambda^{NoSupport}$ and $\lambda^{Support}$ with and without government support for the intermittent technology. The carbon intensity of the mixes of renewable technologies is simply total emissions divided by total output:

$$\lambda = \frac{Emissions}{Output}$$

Comparing the emissions outcomes with and without government support amounts to determining whether the carbon intensity per MWh $\lambda^{NoSupport}$ from the mix of technologies when there is no support for the intermittent technology is larger or smaller than $(1-s)$ times the emissions intensity per MWh with support for the intermittent technology $\lambda^{Support}$.

Result 4 *Government support for an intermittent technology will increase carbon emissions when*

$$s\lambda^{NoSupport} < (1-s)\left(\lambda^{Support} - \lambda^{NoSupport}\right)$$

Proof. Emissions increase when

$$\int_0^1 uEI\left(u\right)\frac{1}{f_n^s\left(F_n^{s-1}\left(1-u\right)\right)}du > \int_0^1 uEI\left(u\right)\frac{1}{f_d\left(F_d^{-1}\left(1-u\right)\right)}du$$

substituting in $\lambda^{NoSupport} = \int_0^1 uEI\left(u\right)\frac{1}{f_d\left(F_d^{-1}(1-u)\right)}du$ and $\lambda^{Support} = \frac{\int_0^1 uEI(u)\frac{1}{f_n^s\left(F_n^{s-1}(1-u)\right)}du}{1-s}$ and rearranging the result follows. ■

This proposition highlights the two potential opposing effects from supporting a clean but intermittent technology. The first is the direct effect from having a carbon free technology generate s% of electricity (the left-hand side), the second and potentially adverse effect comes through changing the efficient mix non-renewable fuels over the remaining $(1-s)$ % of electricity (the right hand side). When the intermittent generation results in a shift towards technologies, which must necessarily be peaking/intermediate technologies (Result 1), with relatively high EI_i then the increase in emissions due to this substitution can more than offset the gains from the direct effect.

4 Estimation

The analysis indicates that in order to assess the long run impact on the mix a generating technologies from a high level of wind penetration one needs an estimate of the joint distribution of wind output (when there is a high level of wind penetration) and electricity demand. This distribution allows one to compare the variability of net load (F_n^s) to electricity demand (F_d). Then given a set of fixed and variable costs for the dispatchable generating technologies this information would provide an estimate of how the mix of generating technologies would change as a result of policies designed to promote a significant amount of investment in wind output.

The ideal data set requires an estimate of the hourly wind output from wind sites which have not been utilised but would be utilised if one were to require a significant amount of output to come from wind. One way in which this can be done is by simulating the hourly profile of potential wind output from historic measurements of weather data at locations within a region which have the greatest wind potential and matching this up against electricity demand. Indeed this type of data has been produced for some regions in North America as part of transmission and operational planning reports to the system operators. The estimation typically involves matching mesoscale weather models to historic weather recordings over a fine grid in the area being analysed.

The next step in the analysis of this paper is to gather this type of data for as many different regions as possible. The emphasis of the analysis is on the choice of generating technology for new power stations and how government policies influence this decision such that the long run mix of technologies is effected. Estimating the change in the mix of technologies requires the costs of these future generating technologies. There is no obvious set of assumptions which is appropriate for this purpose given uncertainty about future technological improvements and other government policy separate from those designed to promote intermittent generation. A reasonable approach is to consider a range of future scenarios for these costs. The theoretic model allows one to infer the scenarios under which wind output will be more or less effective at reducing greenhouse gas emissions. The scenarios where the next generation of baseload technologies have zero or very low GHG emissions such as nuclear and coal with carbon capture and sequestration are the scenarios under which government support for an intermittent technology may be counter productive to a goal of reducing GHG emissions. This is potentially the case in regions where nuclear is/becomes the least cost baseload technology or in the presence of a price on carbon from a cap and trade scheme or carbon tax. If this is the case then renewable portfolio standards and other government policies to subsidize intermittent technologies can be in conflict with a goal of reducing GHG emissions.

5 Conclusion

The contribution of this paper is to highlight how promoting intermittent renewable technologies may have an effect beyond the electricity that is displace by the renewable output. This effect comes through the substitution between non-renewable technologies which meet the electricity demand not covered by the intermittent technology. If the intermittency is sufficiently negatively correlated with electricity demand then non-renewable investment will substitute away from baseload technologies towards peaking/intermediate technologies. When these peaking/intermediate technologies are relatively carbon intensive this may increase total GHG emissions from the electricity sector. In particular policies subsidizing intermittent technologies may be in conflict with an objective to reduce GHG emissions if nuclear power is the least cost baseload alternative or there is a price on GHG emissions and nuclear and/or coal with carbon capture and sequestration are the least cost baseload providers.

References

[1] DeCarolis, J.F. and Keith, D.W., 2006, "The economics of large-scale wind power in a carbon constrained world," *Energy Policy*, 34 (4), pp395-410.