Can wood pellets save coal? Retrofitting coal plants under technological change

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ABSTRACT

A theory of asset replacement is developed to determine the optimal timing and feasible conditions to first rejuvenate and then to replace an asset when a challenger asset is subject to technological change. Technological change impacts capital costs and operation and maintenance costs of a new asset. The theoretical underpinnings mate two strands of research: asset rejuvenation and technological change. With the aid of comparative statistics, results are developed across deterministic costs and matched with conventional asset replacement (no rejuvenation). Co-firing coal with wood pellets is considered as the rejuvenating process. In this context, it is the relative difference in virgin (coal) versus rejuvenation (co-firing) initial costs and growth rates that determines timing and length of rejuvenation.

Keywords: Asset replacement, coal, real options, wood pellets

1. Introduction

Theory surrounding asset replacement has changed greatly since it was first conceived, but this comes with increased understanding of the complex choices that go into making decisions about asset replacement. When considering replacement options, it is more accurate to assume that there are more choices then simply replacing the asset with a new version of the original asset. Often, there is the ability to repair and rejuvenate the asset. Recent research extended this area of study by combining replacement with renewal and used it to study the potential impact this has on replacement decisions for coal fired power plants that could be retrofitted to fire wood pellets.   This research showed that the length of cycles changed when consideration of rejuvenation through co-firing with wood pellets was considered. This is because of the value that exists in extending the plant's life and delaying irreversible replacement (Stutzman et al., 2017) .

Another vein of research has altered the replacement decision through the consideration of technical and legal obsolescence (Hritonenko and Yatsenko, 2008 ; Mardin and Arai, 2012; Mellal et al., 2013; Nguyen et al., 2013; Thi et al., 2010; Yatsenko and Hritonenko, 2011 ; Yatsenko and Hritonenko, 2015). An obvious extension of this research marries rejuvenation/replacement (R/R) with technological change. The first choice becomes when and if to rejuvenate the asset given that a competitor technology exists and has decreasing costs through time because of technological change. This is followed by the choice of when to replace the rejuvenated asset, if rejuvenation was chosen, or when to replace the original asset, if rejuvenation was decided against, with the competitor technology.

A practical application of this development can be seen when considering household decisions surrounding the choice to replace a traditional, gasoline vehicle with a hybrid vehicle. In the 3 years between the initial introduction of the Toyota Prius to the US market and the introduction of the second generation Prius, the estimated yearly fuel consumption of the vehicle decreased by about 34 gallons (EPA, 2012). In this case, a short delay of investment in a hybrid vehicle could have made a significant difference in costs. This idea can be scaled to consider the replacement of individual machines to an entire manufacturing facility with competitor technologies while also considering the possibility of rejuvenation. As a specific application, the R/R problem under technological change can be applied to a coal-fired electric utility plant where the choice exists to either replace with competitor technologies or first rejuvenate the plant and then replace with a competitor.

The aim is to first develop a theoretical model for the rejuvenation and/or replacement of an asset while a competitor technology goes through technological change. Performing comparative statistics reveals the impact of alterations in rate of technological change on the R/R timing and length.

Hypothesis: Under certain conditions, it may be advantageous to rejuvenate a power plant through co-firing. This retrofitting has the ability to extend the life of a power plant, which delays the decision of plant replacement. The ability to delay a decision allows for additional technologies to become less costly alternatives with time. Considering this option value mitigates the cost of rejuvenation making it more attractive.

2. Background

The United States' power supply fleet is aging, with 51% of its power stations over 30 years old. There is a particular issue when looking at large scale utility electricity plants over 250 megawatts. This is because over half of all large scale facilities are coal-fueled and the median age of these facilities is 40 years, with 90% of these facilities over 27 years old (EIA, 2011a). Recent developments in natural gas extraction has dramatically decreased costs of natural gas energy production. As a result, the power sector has been retiring these older coal-fired facilities and building new, natural gas power plants (Strauss, 2017).

This creates conflict with the Trump administration's stated goals of returning jobs to the manufacturing and coal mining sector. The shift from coal-fired to natural gas facilities has poor job retention, as a 400 megawatt coal-fired plant sustains 1686 jobs while a natural gas plant only sustains 576 (Strauss, 2017).

Rather than creating policies to simply maintain current 100% coal-fired power plants, an additional option to help retain and create jobs in both the coal and manufacturing sector is to extend the life of existing coal-fired plants by retrofitting coal with co-fired coal and biomass. Biomass in general, and wood pellets in particular, are a renewable resource, which can be co-fired in coal plants (ACC, 2015; Basu et al., 2011; De and Assadi, 2009; FEMP, 2004; Kinney, 2012; Nicholls and Zerbe, 2012; Zhang et al., 2009). 400 megawatt facilities that co-fire 10% wood pellets are able to sustain 1757 jobs, which is more than firing coal alone. The United States large scale electricity facilities are particular suited for this, as 97% of 250 megawatt or larger plants are pulverized coal facilities Pulverized coal facilities can easily be retrofitted to become co-fired plants, and are just as reliable when modified (Strauss, 2017). While the Trump administration could simply create policy objectives that maintain 100% coal-fired facilities, co-fired facilities have additional benefits. Co-fired power plants not only help maintain jobs in the coal industry and at the power plant, they also spur job creation and retention in the ailing forestry industry and motivate investment spending.

If the administration chose to co-fire all large scale pulverized coal facilities there would be a requirement of 20 million tons of wood pellets. The United States pulp and paper sector has seen increased mill closures, which has resulted in job loss at the mill, logging, and transportation level. Meeting the demand 10% co-fired facilities would create and sustain 32,000 jobs in this area. It would also motivate investment spending in pellet manufacturing facilities to meet demand, with the average cost of a 500,000 ton-per-year pellet plant at $125 million (Strauss, 2017).

In addition to gains in job retention and investment spending, co-fired coal facilities produce fewer GHG emissions and delay the decision to replace a portion of the aging coal firing capacity. This both allows for spreading these costs over longer time periods and competitor technologies, such as solar and wind energy facilities, to decrease in cost, by maintaining the ability to replace the facility at a later date.

Although natural gas prices have been falling in recent years, future prices are uncertain and can be volatile. In addition, with the current median age of large scale power plants in the United States being 40 years, it can be assumed that current large investments in non-renewable power creation, such as natural gas, will only further delay the transition to competitor technologies such as solar. The ability to retrofit aging coal facilities to co-fire wood pellets and extend the life of these plants has some value in delaying the irreversible costs of replacement and allowing the decision maker to observe the realized outcomes of unknown future fuel and investment costs and advancements in competitor assets. Retrofitting coal with co-fired wood pellets may reduce fuel-price uncertainty, through a portfolio effect, but will not eliminate uncertainty, as the costs of retrofitting are largely irreversible. To consider these factors, a model which incorporates the timing for retrofitting and replacement while the cost of a competitor technology decreases is considered.

While Stutzman et al., (2015) examined the dynamic asset replacement with stochastic costs, no studies have looked at how technological change impacts the R/R model. The objective is determining the optimal steady-state R/R sequence under such cases. Additional future modifications of the model and calculations may provide the ability to extend the analysis of coal-fired plant rejuvenation and/or replacement issues to consider different technological change possibilities and legal obsolescence.

3. Rejuvenation/Replacement with Technological Change: Deterministic Case

Let the initial financial outlay costs for a virgin coal-fired power plant be K_1 with rejuvenation costs denoted as K_2. Let K_3 represent the initial cost of the competito technology. Associated with these costs are variable operation costs c_{it},, $i = 1, 2, 3$ with 1 representing costs over the virgin, 2 rejuvenation periods, and 3 competitor period.

Assume these operation costs increase at a constant growth rate of θ_1 for virgin and θ_2 for rejuvenation periods, $c_{1t} = c_{10} \; e^{\theta_1 t}$ and $c_{2t} = c_{20} \; e^{\theta_2 (t - T_1)}$, where c_{i0} denotes virgin and rejuvenation periods' initial operating costs with T_1 and T_2 representing the end of virgin and rejuvenation period, respectively. Assume the operation costs for competitor decrease at a constant growth rate of -θ_3 throughout time, $c_{3t} = c_{30} + c_{40} \; e^{-\theta_3 t}$,where c_{30} denotes the initial operating cost of the competitor period and c_{40} denotes an additional cost of a learning curve that is decreasing through technological change. Denote V as the present value of the R/R cycle and let S represent the residual salvage value, which could be positive or negative. The present value of the R/R cycle can be expressed as

$$(1) \quad V = K_1 + \int_0^{T_1} c_{1t} e^{-rt} \, dt + K_2 \; e^{-rT_1} + \int_{T_1}^{T_2} c_{2t} e^{-rt} \, dt - S \; e^{-rT_2} + K_3 \; e^{-rT_2}$$

$$+ \int_0^{\infty} c_{3t} e^{-rt} \, dt,$$

where r is the discount rate. The first term on the right-hand-side is the initial financial outlay, the second is the present value of virgin operating costs. The virgin power plant is then rejuvenated at a cost of K_2 followed by the present value of rejuvenated operating costs. The present value of the salvage value is taken into account as the present value of financial cost of the competitor technology is considered. Finally, the operating costs of the competitor technology are considered into perpetuity, eventually decreasing to c_{i0}. It is assumed that that with solar energy that complete replacement of the facility is not considered, and, instead, individual solar panels are upgraded or replaced through time. These costs are represented in operating and maintenance costs.

The optimal length of the virgin period, T_1, and the end of rejuvenated period, T_2, can then be determined by

$$\text{(2a)} \quad \frac{\partial V}{\partial T_1} = c_{1T_1} e^{-rT_1} - r K_2 \; e^{-rT_1} - c_{2T_1} e^{-rT_1} - c_{3T_1} e^{-rT_1} = 0.$$

$$\text{(2b)} \quad \frac{\partial V}{\partial T_2} = c_{2T_2} e^{-rT_2} + r \; S e^{-rT_2} - r \; K_3 e^{-rT_2} - c_{3T_2} e^{-rT_2} = 0.$$

In (2a) it is assumed initial operating costs are not affected by a time delay in rejuvenation, $\partial c_{2t}/\partial T_1 = 0$. Simplifying (2a)

$$c_{1T_1} = rK_2 + c_{2T_1} + c_{3T_1} .$$

At the optimal T_1, the cost in the last virgin time period must just equal the cost of delaying the recycle period plus the first time period rejuvenation cost plus competitor technology cost in that time period. Substituting $c_{1T_1} = c_{10} e^{\theta_1 T_1}$, $c_{2T_1} = c_{20}$, and

$$c_{3T_1} = c_{30} + c_{40} e^{-\theta_3 T_1} .$$

$$\text{(3)} \quad c_{10} e^{\theta_1 T_1} = rK_2 + c_{20} + c_{30} + c_{40} e^{-\theta_3 T_1}$$

Condition (3) leading to the solution for optimal T_1 is nonlinear, requiring numerical analysis to solve for the optimal solution. However, comparative statics are possible and presented below.

Proposition 1: The terminal virgin period, T_1, response to the parameters are:

$$\frac{dT_1}{d\theta_1} < 0, \quad \frac{dT_1}{d\theta_3} < 0, \quad \frac{dT_1}{d\theta_2} = \frac{\partial T_1}{\partial K_1} = \frac{\partial T_1}{\partial K_3} = \frac{dT_2}{dS} = 0, \quad \frac{dT_1}{dc_{10}} < 0,$$

$$\frac{dT_1}{dc_{20}} > 0, \quad \frac{dT_1}{dc_{30}} > 0, \quad \frac{dT_1}{dc_{40}} > 0, \quad \frac{dT_1}{dr} > 0, \text{ and } \frac{dT_1}{dK_2} > 0.$$

Condition (2b) also has a non-linear simplification, presented below as condition (4), when determining the optimal T_2. The associated level of operation costs that trigger recycling of the facility and replacement with a competitor are $c_{2T_2} = c_{20} e^{\theta_2 T_2}$ and $c_{3T_2} = c_{30} + c_{40} e^{-\theta_3 T_2}$.

(4) $c_{20} e^{\theta_2 T_2} = rK_3 - rS + c_{30} + c_{40} e^{-\theta_3 T_2}$

Although an analytic solution is not possible in this case, some comparative statics are presented in Proposition 2.

Proposition 2: The terminal rejuvenation period, T_2, response to the parameters are:

$$\frac{dT_2}{d\theta_2} < 0, \quad \frac{dT_2}{d\theta_3} < 0, \quad \frac{dT_2}{d\theta_1} = \frac{\partial T_2}{\partial K_1} = \frac{dT_1}{dK_2} = \frac{dT_1}{dc_{10}} = 0, \quad \frac{dT_2}{dc_{20}} < 0,$$

$$\frac{dT_2}{dc_{30}} > 0, \quad \frac{dT_2}{dc_{40}} > 0, \quad \frac{dT_2}{dS} < 0, \text{ and } \frac{dT_2}{dK_3} > 0. \quad \frac{dT_2}{dr} \text{ is ambiguous.}$$

The first thing to notice is that the virgin outlay costs, K_1, comparative statics indicated that it has no impact on the initial power plant's total life when considering technological change of a competitor asset, regardless if it is rejuvenated. This differs from the R/R deterministic model considered in Stutzman et al. (2017) where it was found that an increase in virgin outlay cost, K_1, would increase the total cycle, not by increasing the virgin production period, but by increasing the rejuvenation period. This is because the original facility is not being replaced by the original asset in the R/R with technological change model, but is being replaced by a competitor asset, so the virgin outlay cost will not be incurred again. The residual salvage value S does impact the total cycle in this case, with S negatively related to total plant life. Although S does not influence the virgin period length (3), it does affect the rejuvenation period length (4). This is in contrast to the rejuvenation outlay cost, K_2, where the virgin period is now generally positively influenced by this cost. The impact of the rejuvenation outlay cost on the rejuvenation period is not revealed by the comparative statics, but the lifespan of the initial power plant increases by increasing the virgin period length.

The initial outlay cost of the competitor technology, K_3, has no impact on the length of the virgin period, but can increase the total life of the initial asset. This is because the impact of the competitor outlay cost has a positive influence on the length of the rejuvenation period, T_2. An increase in the initial outlay cost of the competitor will increase the length of the rejuvenation period, while causing no change on the virgin period, increasing the total lifespan of the initial power plant.

It was seen in Dobbs (2004) that when considering conventional replacement there exists a positive relationship between virgin initial operating costs, c_{10}, and the total cycle. However, the opposite can occur when rejuvenation with technological change is considered. In this case, the virgin period length, T_1, is shortened with an increase in its initial operating costs. This result makes sense when a competitor technology and rejuvenation are introduced to the model. This is caused by the interplay between virgin and rejuvenation costs and virgin and competitor costs. Very similar results occur for the virgin operating cost growth rate, θ_1, where an increased growth rate for the virgin period will shorten the time before rejuvenation and shorten the total life of the initial power plant before the competitor technology is adopted.

In this case, the virgin period length is positively related to changes in c_{20}, so T_1 does increase for an increase in c_{20}. As a result, the life of the initial asset would decrease with an increase in the initial operating cost during the rejuvenation period.

The rejuvenation growth rate, θ_2, just as the residual salvage value, *S*, only affects the rejuvenation period. An increase in either will decrease the rejuvenation period, T_2, and lead to an earlier transition to the competitor asset.

The length of both the virgin and rejuvenation period is responsive to an increase in the initial operating cost of the competitor technology, c_{30}. This is the result of the competitor technology becoming cheaper through time and while the initial asset is in use. An increase in the initial operation cost of the competitor will increase the life of the initial asset by increasing the length of both the virgin and rejuvenation periods. The same is true for the initial cost of the learning curve of the new technology, c_{40}. The steeper the learning curve, and the higher the initial cost associated with it, the longer both the virgin and rejuvenation periods and the total life of the initial power plant. The rate of technological change, θ_3, also will influence both the virgin and rejuvenation periods, but negatively. If the rate of technological change in the competitor asset is increased this will decrease the total life of the initial asset by decreasing both T_1 and T_2.

Finally, comparative statics does not reveal the effect of the discount rate, r, on the rejuvenation period. It is believed that, just as in Stutzman et al. (2017), the more elastic T_1 is to *r* the greater the likelihood $\frac{dT_2}{dr}>0$, and an increase in the discount rate would increase the virgin period, T_1, and the total life of the initial asset. In the future, numerical analysis can be employed to reveal the parameter influences.

These statics results indicate the marked difference the parameters have on the optimal length of cycles when comparing the conventional and R/R with technological change decisions. For conventional replacement, Dobbs (2004) showed that relatively high virgin outlay costs, K_1, and virgin initial operating costs, c_{10}, along with a low residual salvage value, S, will result in a longer plant life. While low residual salvage value, S, will also yield a longer life of the initial asset when R/R with technological change is considered, the virgin outlay costs, K_1, has no impact on the lifespan of the initial asset. However, higher initial operating costs, c_{10}, leads to a shorter virgin period length and has an ambiguous effect on the length of the total life of the initial asset. The interplay of virgin and rejuvenation costs and virgin and competitor costs is responsible for the difference in these results.

4. Conclusions

The theory for determining the optimal times under an asset rejuvenation/replacement sequence with technological change is developed in a dynamic context. A deterministic model for asset rejuvenation and then replacement is determined. The differences between pure replacement and R/R under technological change are illustrated through comparative statics results. Leading to these differences in the comparative statistics results are the interplay of the relative costs between the initial non-rejuvenation and rejuvenation periods and between the initial non-rejuvenation and the competitor technology. The relative difference in costs in each stage can be seen to play an important role in determining the optimal time to rejuvenate the asset and to replace the asset with a competitor technology that is becoming cheaper through time.

The development of the deterministic model paves the way for construction of a stochastic model that incorporates both rejuvenation and replacement decisions and a competitor asset that is going through technological change. Development of the stochastic model will also allow for numerical analysis using data on coal-fired, co-fired, and solar power plants. This will lead to a better understanding of how co-firing with wood pellets can aid in the transition away from non-renewable energy sources while fitting into the Trump administrations plans for maintaining jobs in the American coal and manufacturing industries.

References

ACC. 2015. “Biomass co-firing with coal as an emission reduction strategy,” American Coal Council,
http://www.americancoalcouncil.org/?page=biomass

Adkins, R. and D. Paxson. 2011. “Renewing Assets with Uncertain Revenues and Operating Costs,” Journal of Financial and Quantitative Analysis 46(3): 785-813.

Basu, P., J. Butler, and M. Leon. 2011. "Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants," Renewable Energy 36(1): 282-288.

Burt, O. 1965. “Optimal replacement under risk,” Journal of Farm Economics 47:324-346.

Campbell, R., P. Folger, and P. Brown. 2013. “Prospects for Coal in Electric Power and Industry,” Congressional Research Service, 7-5700.
https://www.fas.org/sgp/crs/misc/R42950.pdf

Chisholm, A. 1966. “Criteria for determining the optimum replacement pattern,” Journal of Farm Econmics 48:107-112.

De, S., and M. Assadi. 2009. "Impact of cofiring biomass with coal in power plants–A techno-economic assessment," Biomass and Bioenergy 33(2): 283-293.

Dobbs, I. 2004. “Replacement investment: Optimal economic life under uncertainty,” Journal of Business Finance and Accounting 31:729-757.

E&E Publishing, LLC. 2016. “E&E E&E’s Power Plan Hub: Indiana”
http://www.eenews.net/interactive/clean_power_plan/states/indiana

EIA. 2011a. “Age of electric power generators varies widely,” Today in Energy, U.S. Energy Information Administration, June16, 2011.
http://www.eia.gov/todayinenergy/detail.cfm?id=1830

EIA. 2011b. “Most coal-fired electric capacity was built before 1980,” Today in Energy, U.S. Energy Information Administration, June28, 2011.
https://www.eia.gov/todayinenergy/detail.cfm?id=1990

EIA. 2013. “Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants.” April 2013.http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf

EIA. 2014. “AEO2014 projects more coal-fired power plant retirements by 2016 than have been scheduled,” Today in Energy, U.S. Energy Information Administration, Februarys 4, 2014.
http://www.eia.gov/todayinenergy/detail.cfm?id=15031

EIA. May 22, 2015. “Analysis of the Impacts of the Clean Power Plan.”
https://www.eia.gov/analysis/requests/powerplants/cleanplan/

EIA. 2016. Electricity Data Browser. http://www.eia.gov/electricity/data/browser/

Faustmann, M. 1968. “On the determination of the value which forest land and immature stands possess for forestry,” Oxford Institute, paper 42, ed. M. Gane. Oxford, UK.

FEMP. 2004. “Biomass cofiring in coal-fired boilers,” Federal Energy Management Program, Federal Technology Alert, DOE/EE-0288.
http://www.nrel.gov/docs/fy04osti/33811.pdf

Hritonenko, N. and Y. Yatsenko. 2008. “The dynamics of asset lifetime under technological change,” Operations Research Letters 36: 565-568.

Ibendahl, G., M. Farrell, S. Spurlock, and J. Tack. 2014. “Optimal replacement age of a conventional cotton harvester system,” Agricultural Finance Review 74(1): 2-16.

IRENA. 2012. “Biomass for Power Generation.” Renewable Energy Technologies: Cost Analysis Series. International Renewable Energy Agency. Working paper. Vol 1: Power Sector. Issue 1/5. June 2012.
http://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf

IRENA. 2013. “Biomass Co-firing” IEA-ETSAP and IRENA Technology Brief E21. January 2013. http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E21%20Biomass%20Co-firing.pdf

Kinney, S. 2012. Wood bioengery and natural gas prices. F2M Market Watch, June 11, 2012. http://www.forest2market.com/blog/Wood-Bioenergy-and-Natural-Gas-Prices

Mauer, D. and S. Ott. 1995. “Investment under uncertainty: The case of replacement investment,” Journal of Financial and Quantitative Analysis 30:581-605.

McClelland, J., M. Wetzstein, and R. Noles. 1989. “Optimal replacement policies for rejuvenated assets,” American Journal of Agricultural Economics 71(1):147-157.

McLaughlin, R. and R. Taggart. 1992. “The opportunity cost of using excess capacity,” Financial Management 21:12-23.

Nicholls, D. and J. Zerbe. 2012. “Cofiring biomass and coal for fossil fuel reduction and other benefits: status of North American facilities in 2010. U.S.D.A., Forest Service, General Technical Report, PNW-GTR-867, August 2012. http://www.fs.fed.us/pnw/pubs/pnw_gtr867.pdf

Perrin, R. 1972. “Asset replacement principles,” American Journal of Agricultural Economics, 54(1): 60-67.

David G. Nderitu, Paul V. Preckel, Douglas J. Gotham, Elizabeth A. Dobis, “Assessment of the National Prospects for Electricity Generation from Biomass”, Purdue University, State Utility Forecasting Group, April 2014

Reindorp, M. and M. Fu. 2011. “Capital renewal as a real option,” European Journal of Operational Research 214:109-117.

Samuelson, P. 1937. “Some aspects of the pure of capital,” Quarterly Journal of Economics 51:469-96.

Schlissel, D., A. Smith, R. Wilson. 2008. Coal-Fired Power Plant Construction Costs. Synapse Energy Economics, Inc., July.

Sekar, R., J. Parsons, H. Herzog, H. Jacoby. 2007. "Future carbon regulations and current investments in alternative coal-fired power plant technologies." Energy Policy 35.2 (2007): 1064-1074.

Smith, G. and M. Wetzstein. 1992. “A stochastic asset replacement model for rejuvenated assets,” American Journal of Agricultural Economics 74(2): 378-87.

Spelter, H., D.Toth. 2009. North America's wood pellet sector: USDA, Forest Service, Forest Products Laboratory.

Strauss, W. 2017. “How Trump could save coal with wood pellets.” Biomass Magazine. Available at: http://www.biomassmagazine.com/articles/14245/how-trump-could-save-coal-with-wood-pellets

Stutzman, S., B. Weiland, P. Preckel, and M. Wetzstein. 2017. “Optimal replacement policies for an uncertain rejuvenated asset.” International Journal of Production Economics 185: 21 – 33.

Venere, Emmil. January 25, 2012. “Indiana electricity rates projected to rise from new clean-air rules”. University News Service. Purdue University. Available at: http://www.purdue.edu/newsroom/research/2012/120125GothamCleanair.html

Xian, H., G. Colson, B. Mei, and M. Wetzstein. 2015. "Co-firing coal with wood pellets for US electricity generation: A real options analysis," Energy Policy 81: 106-116.

Zhang, Y., J. McKechnie, D. Cormier, R. Lyng, W. Mabee, A. Ogino, H. MacLean. 2009. Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. Environmental science & technology. 44, 538-544.