Punctuated Equilibrium:
Application of Hydraulic Fracturing Innovations for Enhanced Geothermal Systems

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Background:

The theories of punctuated equilibrium and diffusion are widely studied, often congruently. Punctuated equilibrium describes the sudden shift from the incumbent technology to the new technology, while diffusion refers to the spread of a technology that leads to the punctuation. The main focus of punctuated equilibrium and diffusion research is between two competing technologies, one incumbent and one new, and their penetration in a specific market. Less focused upon, however, are punctuations and diffusions of a single technology across industries. Here, we adapt the model described in by Loch and Huberman.[1] The L&H model studies technology diffusion and punctuation of a new technology when it is competing with an established technology. As innovation naturally cycles through industries, short and sudden punctuations can occur, signifying a major shift from an old technology to a new technology. Punctuations are more likely to occur if there are external benefits associated with the technology, thereby making the adoption beneficial to the user, and if one technology's performance is superior over the other.

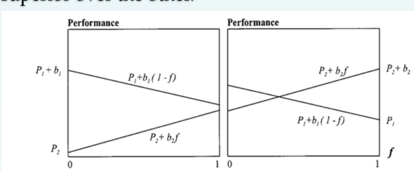

Figure 1: At a fixed point in time, a technology with inferior benefits and performance will not surpass the incumbent, as shown on the left. On the right however, a new technology will cross over the first become superior when adopted by all firms in the industry (when it reaches "critical mass").

Initial uncertainties associated with adopting the technology also increase the likelihood of adoption, as do high learning-rates and the speed at which users adopt the technology. The L&H model assumes that decision makers are profit-driven and only choose the best of the available technology.

Punctuated equilibrium is often studied in regard to *competing technologies in the same industry*. In this model, we propose that the diffusion and punctuation patterns will be evident when applied to *a single technology's market penetration across industries*, giving new insight to cross-industry technology transfer.

Methods:

To conduct this analysis, we use hydraulic fracturing technology as a case study. Hydraulic fracturing, combined with horizontal drilling, has created a boom in natural gas production from shale rock. It has also been suggested that hydraulic fracturing technology could be utilized in Enhanced Geothermal Systems (EGS) drilling.[2]

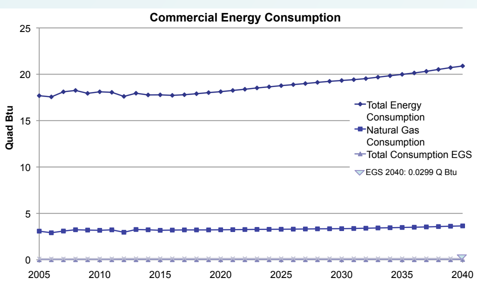

Figure 2: The EIA projects growth in commercial energy consumption from both the natural gas and EGS sectors.

The Model:

In our model, the performance of the a technology (hydraulic fracturing) is calculated for both the EGS and the natural gas industry. We hypothesize that EGS will benefit and have a higher learning rate due to the advancements of hydraulic fracturing technology in the natural gas drilling industry.

The metrics of interest are change in the percent of firms, f, using the technology over time, t (eq.1) and the performance, P, of the each industry (eq.2). These metrics are dependent on equations 3-5, where b is benefit, n is the probability of each industry choosing the technology, D is the distance between each performance, and B is uncertainty. We analyze the potential market penetration of fracking, in terms of the percent of EGS firms using fracking technology. Performance is characterized by the total cost of constructing a power plant (natural gas and geothermal), in \$/GWh. A full list of parameters and descriptions is seen in Table 1.

$$\frac{df}{dt} = a\left[(1-f)n_2(f) - fn_1(f)\right] \quad (1)$$

$$P_i(t) = P_i(t) + c_i f_i(t) P_i(t) \frac{P - \bar{P}_i(t)}{\bar{P}_i} \quad (2)$$

$$n_2(f) = 0.5e^{-BD(f)} \text{ if industry 1 is better} \quad (3)$$

$$n_1(f) = 1 - 0.5e^{BD(f)} \text{ if industry 2 is better} \quad (4)$$

$$D = P_1 + b_1 - P_2 - (b_1 + b_2)f \quad (5)$$

Results:

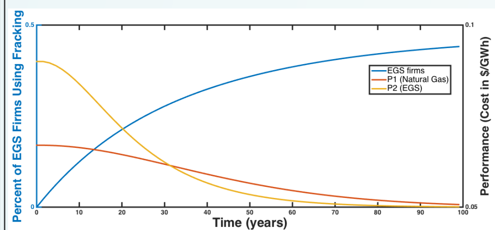

Figure 3: Performance in Terms of Cost: Fracked Natural Gas vs. EGS

The results of our model show that over time, performance, in terms of total cost (\$/GWh) of a power plant, improves for both natural gas-fired and EGS power plants, meaning the drilling and construction costs become less expensive, as indicated by the y-axis on the right. The model estimates that approximately 30 years from now, utilizing fracking technology in EGS operations leads to EGS having a better performance than natural gas. Additionally, as EGS performance increases, the percent of EGS firms using fracking technology in the industry increases as well, as indicated by the y-axis on the left.

Table 1: Model Parameters

Parameters	Notation	Value	Notes
Time	t	01:05.5	Defines total time & steps of simulation
Percent of EGS firms using the technology	f(t=1)	0	Assuming no EGS firms are currently using fracking technology
Positive externality associated with natural gas	b1	12.98%	Projected total energy consumption from fracked natural gas in 2040 [3, 7]
Positive externality associated with EGS	b2	2.83%	Projected total energy consumption from EGS in 2040 [3, 4]
Uncertainty of the technology	b	0.5	Using the assumption from L&H model [1]
Rate at which actors evaluate technology performance	a	0.05	Using the Poisson assumption from L&H model [1]
Initial technology performance in natural gas industry	P1-initial	0.067	Total cost, in \$/GWh, of a natural gas-fired power plant [5]
Initial technology performance in geothermal industry	P2-initial	0.09	Total cost, in \$/GWh, of a geothermal power plant [5]
Mean technology performance	P1-mean	0.05	Total cost, in \$/GWh, assuming that performance will improve over time
Mean technology performance	P2-mean	0.05	Total cost, in \$/GWh, assuming that performance will improve along with natural gas performance (P1)
Learning rate	c1-initial	0.07	In terms of cost, developmental oil & gas wells are 7-18% less expensive than exploratory wells [6]
Learning rate	c1-max	0.18	
Learning rate	c2	0.25	In terms of cost, developmental EGS wells are 25% less expensive than exploratory wells [6]

Sensitivity Analysis:

A sensitivity analysis shows that the percent of EGS firms using fracking is most sensitive to the benefits of fracking in the natural gas industry (b1), evaluation of performance (a), and uncertainty (B). Performance of natural gas is most sensitive to it's learning curve (c1), as is performance of EGS is most sensitive to it's learning curve (c2).

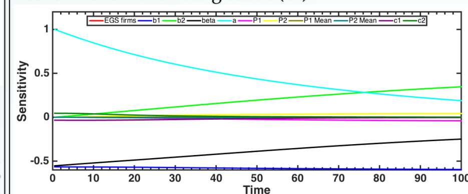

Figure 4: Sensitivity – Percent of EGS Firms Using Fracking

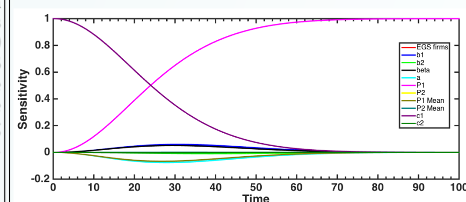

Figure 5: Sensitivity – Performance of Natural Gas (P1) in Terms of Cost

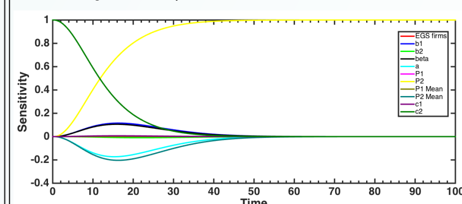

Figure 6: Sensitivity – Performance of EGS (P2) in Terms of Cost

Implications for Future Work:

The model implies that EGS may benefit from utilizing fracking technology. Additional research will focus on alternative variables for the model, as well as testing the model for an established technology transfer. For example, the widespread adoption in the 1980s of gas turbines over steam turbines for power generation is viewed as a punctuation.

References:

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