# Sequential Investment in Emerging Technologies under Risk Aversion and Policy Uncertainty

Lars Hegnes Sendstad[1]
Lars.sendstad@nhh.no
+47 90 07 91 17

Petter Bjerksund[2]
Petter.Bjerksund@nhh.no
+47 55 95 95 48

Michail Chronopoulos[3]
Michail.Chronopoulos@nhh.no
+47 55 95 92 66

Investment in emerging technologies is often made in the light of uncertainty in both the arrival of new versions and the revenue that may be earned from their deployment. Further complicating such investment decisions is that the future development of emerging technologies depends crucially on government support, yet the absence of a clear policy framework increases uncertainty in revenue streams. We show how a firm can optimally take advantage of the flexibility over the investment timing and the technology adoption strategy facing price, technological, and policy uncertainty. More specifically, we analyse the impact of these features on the optimal investment decision, and, in particular, we illustrate the relative value of each type of discretion for a risk-averse decision maker, thereby capturing real-world attributes shaping decision making such as costs of financial distress and shareholder constraints over borrowing. Although the incentive to delay investment increases as both price uncertainty and the level of risk aversion increase, whether the sudden provision of a subsidy or the potential to replace equipment with more efficient ones mitigates the impact of price uncertainty and risk aversion remains an open question.

Indeed, a gap in the real options framework is that it assumes that financial markets are complete, and, therefore, that the investor is risk neutral. However, for projects that involve undiversifiable risks, such as R&D of new products, risk aversion on part of investors should be considered. Nevertheless, much of the real options framework has been developed under the assumption of complete markets, which is the underlying assumption of contingent claims analysis.  However, with the increasing amount of investment in emerging markets and new R&D-based sectors of the economy, such as renewable energy (RE) technologies, the assumption of hedging via spanning assets breaks down as the underlying commodities are not likely to be freely traded. Hence, risk-neutral valuation may not be possible and dynamic programming, can then be used to maximize the expected utility of the lifetime profits of a risk-averse decision maker. Examples that indicate risk-averse behaviour include Black Berry that was once the industry standard for professional users. They relied on their reputation for security and a full QWERTY keyboard, but were slow to recognize the value of the apps (Harvard Business Review, 2013). Another example is Kodak, that was reluctant to adapt to the digital age, and unlike its competitor Fujifilm eventually went bankrupt (The Economist, 2012). The impact of risk aversion on investment decisions has been analysed by Henderson and Hobson (2002), who extend Merton (1969) by taking the perspective of a risk-averse decision maker facing incomplete markets. Henderson (2007) explores the effects of risk aversion on investment timing and option value by utilizing an exponential utility function, and finds that increasing risk aversion may accelerate investment. Hugonier and Morellec (2013) use the analytical framework of Karatzas and Shreeve (1999) in order to determine the analytical expression of the expected

[1] Norwegian School of Economics, Department of Business and Management Science, Bergen, Norway
[2] Norwegian School of Economics, Department of Business and Management Science, Bergen, Norway
[3] Norwegian School of Economics, Department of Business and Management Science, Bergen, Norway

utility of a perpetual stream of cash flows that follow geometric Brownian motion (GBM) and express the investment policy as the solution to an optimal stopping problem. Chronopoulos *et al*. (2011) extend Hugonier and Morellec (2013) and show that increased operational flexibility mitigates the impact of risk aversion. Alvarez and Stenbacka (2003) show that price uncertainty does not necessarily decelerate investment. Note that these papers address the impact of risk aversion on investment and operational decisions allowing only for price uncertainty, and, as a result, the implications of technological and policy uncertainty remain underdeveloped.

Although risk aversion reduces the expected utility of a project, and, in turn, the investment incentive, the likelihood of subsidy provision may facilitate investment. For example, Tesla chose to build its battery factory in Nevada due to a special tax provision of $1,25 billion dollar over 20 years (CNBC, 2014). While Spain retroactively capped its RE subsidies, causing Spain's second biggest wind operator to state that this will destroy their RE investments (Bloomberg, 2014). The subsidy induced early investment in Spain under the understanding that the subsidy would be long lasting. Examples of policy oriented papers include Boomsma *et al.* (2012), who explore how the investment decision is affected by different support schemes, namely feed-in tariffs and RE certificate trading. They find that, policy uncertainty can positively affect both investment timing and capacity sizing decisions. Adkins and Paxson (2013) model the random provision and retraction of a subsidy via a Poisson process and develop an analytical model for investment under price and quantity uncertainty. They investigate five cases: no subsidy, permanent subsidy without policy uncertainty, sudden subsidy retraction, sudden provision of a permanent subsidy, and finally a sudden provision of a retractable subsidy. They find that the presence of a subsidy lowers the investment threshold and that the sudden retraction of a subsidy facilitates investment. This reflects the fact that it is beneficial for the firm to take advantage of the subsidy while it is still active. In the fourth case, sudden provision of a permanent subsidy increases the investment threshold considerably. In the last model, if the current price is out-of-the-money the value is similar to the third case. Additionally, the value of the option to invest increases as the correlation between the price of electricity and quantity of electricity produced increases, since this raises the aggregate volatility. Although these papers address the impact of policy uncertainty on investment in RE power plants, they ignore the implications of risk aversion or how technological innovations provide the opportunity for sequential investment, thereby creating considerations for technology adoption strategies.

Examples of analytical frameworks for sequential investment under risk neutrality include Majd and Pindyck (1987), who demonstrate how traditional valuation techniques understate the value of a project by ignoring the flexibility in the time to build. Dixit and Pindyck (1994) utilize a GBM and develop a model for sequential investment assuming that the project value depreciates exponentially and the investor has an infinite set of options. In the same line of work, Gollier *et al*. (2005) demonstrate how the value of modularity may induce investment even below the now-or-never NPV threshold, while Kort *et al*. (2010) show that higher price uncertainty can make a lumpy investment more attractive compared to a more flexible yet more costly stepwise investment strategy. Allowing for technological uncertainty, Balcer and Lippman (1984) find that expectations regarding the arrival of innovations affect the investment decisions and that technological uncertainty may delay investment. Grenadier and Weiss (1997) develop a model for sequential investment, whereby a firm may either adopt every technology that becomes available (compulsive), skip an old technology in order to adopt the next one (leapfrog), purchase only an early innovation (buy and hold), or wait for a new technology to arrive before adopting the previous one (laggard). Farzin *et al*. (1998) model technological uncertainty via a Poisson process yet ignore price uncertainty, while Doraszelski (2001) identifies a mistake in Farzin *et al*. (1998) and shows that a firm will defer investment when it takes the value of waiting into account. Chronopoulos and Siddiqui (2014) develop an analytical framework for sequential investment in emerging technologies and analyse how the endogenous relation between price and technological uncertainty impacts the optimal technology adoption strategy and the associated investment rule. While these papers present a comprehensive modelling of investment in technological innovations, they assume a risk-neutral decision maker, and, as a result, the impact of risk aversion is not taken into account.

In this paper, we take the perspective of a risk-averse decision maker and develop real options framework for sequential investment under price, policy, and technological uncertainty. Thus, we extend the existing literature on investment under uncertainty, that either allows for risk aversion without considering policy or technological uncertainty or takes into account the impact of these features under risk neutrality. Following the approach of Hugonier and Morellec (2013), we can derive the expected utility of cash flows that follow GBM via Theorem 9.18 of Karatzas and Shreeve (1999) and then formulate sequential investment opportunities as a nested optimal stopping time problem. In addition, we assume that policy and technological uncertainty are modelled via independent Poisson processes. The former reflects the sudden provision or retraction of a subsidy, whereas the latter reflects the random arrival of innovations. By incorporating such features in an analytical framework for sequential investment, we can prove insights not only on how price, policy, and technological uncertainty interact to affect the optimal technology adoption strategy of a risk-averse decision maker, but also on how this may provide a feedback that will enable policy makers to devise more efficient policy mechanisms.

In an era of great financial volatility, firms in sectors such as energy, manufacturing, and telecommunications require managerial strategies that are responsive to market conditions. Indeed, the implications of the structural transformation of the power sector for both market participants and policy makers are expected to be crucial as they will change substantially the wholesale market dynamics (Sensfuß *et al*., 2008). Within this environment, private firms are required to make accurate investment decisions, while policymakers must take into account how private firms respond to price, technological, and policy uncertainty in order to incentivise investment. Hence, the contribution of this work is in delineating the value of flexibility when a firm faces both external, e.g., market, technological, and policy uncertainty, as well as internal, e.g., risk constraints, pressures.

**References:**

Adkins, R, and D Paxson (2013), “Subsidies for Renewable Energy Facilities under Uncertainty,” *working paper*.

Alvarez, LHR., and R Stenbacka (2003), “Optimal Risk Adoption: A Real Options Approach,” *Economic Theory* 23(1): 123–47.

Balcer, Y, and SA Lippman (1984), “Technological Expectations and Adoption of Improved Technology,” *Journal of Economic Theory* 34(2): 292–318.

Bloomberg (2014), “Spain Caps Earnings from Renewables in Subsidy Overhaul,” 6 June.

Boomsma, TK, Meade N, and S Fleten (2012), “Renewable Energy Investments under Different Support Schemes: A Real Options Approach*,” European Journal of Operational Research* 220(1): 225–37.

Chronopoulos, M, BD Reyck, and A Siddiqui (2011), "Optimal Investment under Operational Flexibility, Risk Aversion, and Uncertainty," *European Journal of Operational Research* 213(1): 221–37.

Chronopoulos, M, and A Siddiqui (2014), "When Is It Better to Wait for a New Version? Optimal Replacement of an Emerging Technology Under Uncertainty," *SSRN Scholarly Paper. Rochester, NY: Social Science Research Network.*

CNBC (2014), "Nevada Wins Tesla Plant, but at What Cost?," 5 September.

Dixit, AK, and RS Pindyck (1994), "Investment under Uncertainty," *Princeton, N.J: Princeton University Press.*

Doraszelski, U (2001), "The Net Present Value Method versus the Option Value of Waiting: A Note on Farzin, Huisman and Kort (1998)," *Journal of Economic Dynamics and Control* 25(8): 1109–15.

Farzin, YH, KJM Huisman, and PM Kort (1998), "Optimal Timing of Technology Adoption," *Journal of Economic Dynamics and Control* 22(5): 779–99.

Gollier, C, D Proult, F Thais, and G Walgenwitz (2005), "Choice of Nuclear Power Investments under Price Uncertainty: Valuing Modularity," *Energy Economics* 27(4): 667–85.

Grenadier, SR, and AM Weiss (1997), "Investment in Technological Innovations: An Option Pricing Approach," *Journal of Financial Economics* 44(3): 397–416.

Harvard Business Review (2013), "Blackberry Forgot to Manage the Ecosystem," 19 August.

Henderson, V, and DG Hobson (2002), "Real Options with Constant Relative Risk Aversion," *Journal of Economic Dynamics and Control* 27(2): 329–55.

Henderson, V (2007), "Valuing the Option to Invest in an Incomplete Market," *Mathematics and Financial Economics* 1: 103–28.

Hugonnier, J, and E Morellec (2013), "Real Options, Ambiguity, Risk and Insurance: World Class University Program in Financial Engineering Ajou University," *Ios Pr Inc, Amsterdam*: 55-65.

Karatzas, I, and S Shreve (1999), "Methods of Mathematical Finance," *Springer Verlag, New York NY, USA.*

Kort, PM, P Murto, and G Pawlina (2010), "Uncertainty and Stepwise Investment," *European Journal of Operational Research* 202(1): 196–203.

Majd, S, and R S Pindyck (1987), "Time to Build, Option Value, and Investment Decisions," Journal of Financial Economics 18(1): 7–27.

Merton, RC (1969), "Lifetime Portfolio Selection under Uncertainty: The Continuous-Time Case," *The Review of Economics and Statistics* 51(3): 247–57.

Sensfuß, F, M Ragwitz, and M Genoese (2008), "The Merit-Order Effect: A Detailed Analysis of the Price Effect of Renewable Electricity Generation on Spot Market Prices in Germany," *Energy Policy*, 36(8): 3076-3084.

The Economist (2012), “The Last Kodak Moment?” 14 January.