The Effect of Investment Potential and Financing on Investments and the Elasticity of Supply

Svetlana A. Ikonnikova[*], Victor del Carpio Neyra[†], Sofia Berdysheva[‡]

Highlights

- We study investment behaviour of a value-maximizing firm, which balances its profitability and expansion of its future production capabilities.
- We examine the effect of price and technology expectations, financial deficit, and project characteristics, including profitability and investment potential, on supply.
- We derive the price elasticity of supply as a function of current and future prices focusing on differences in responses for established projects with limited investment potential and new ones.
- We explain the negative elasticity of supply phenomenon and highlight how the share of innovative projects may be affected by the constraints imposed on the established projects.

Abstract

This paper studies 1) the interplay of factors determining project and capacity choices, namely financial deficit, investment potential, price and technology expectations, and derives 2) the relationship between investment and the elasticity of supply dynamics. Our goal is to understand what incentivizes firms to invest in novel technologies, characterized by low (or negative) returns, forgoing high-profitability projects, and why the price reactions of seemingly similar firms may differ. With insights from the U.S. unconventional industry, we develop an investment model to analyse the trade-off between profit generation and expansion of production potential. The solution reveals how project characteristics, especially growth potential and associated uncertainty, affect the portfolio along with technology and price expectations.

Next, we use the investment model results to derive the price elasticity of supply. The results explain a diversity in price responses by the differences in project characteristics, financial capabilities, and expectations. Thus, the negative elasticity or a "backward bending" supply curve phenomenon can be explained by price and technology expectations, whereas inelastic supply by financial deficit, vast investment potential, and high learning ability. The comprehensiveness of our approach accommodates the diversity of insights about supply and investment dynamics and we believe, is essential for projecting the energy transition.

Keywords: investment allocation, price expectations, innovations, elasticity of supply, energy

[*] School of Management at the Technical University of Munich; the Center for Energy Economics, the Bureau of Economic Geology at the University of Texas at Austin. Email: Svetlana.ikonnikova@tum.de. Corresponding author.

[†] The Center for Energy Economics, the Bureau of Economic Geology at the University of Texas at Austin

[‡] School of Management at the Technical University of Munich, Center for Energy Markets.

1. Introduction

Climate change problems have prompted an increasing number of countries to set carbon targets and impose regulations encouraging investments in low-carbon technologies. Firms face technology and capacity choices and numerous trade-offs associated with investment decisions. The energy transition contributes to input and output price changes, affecting profits and limiting firms' ability to finance new projects. The problem of financing is aggravated by the low and, in some cases, negative profitability of new technology projects, like green hydrogen production. To benefit from the economies of scale, learning, and technological advances boosting productivity and reducing costs, producers have to start investing in developing those new projects (Deign, 2019). Investment decisions are further complicated by productivity differentiation coupled with limitations in projects' capacity and availability. Thus, renewable wind and solar projects vary in their generation potential across geographical areas and are limited by the locations available for installations, especially onshore. Firms have to decide whether to invest in more productive projects compensating for the high present-day costs and keep the lower production potential projects for later until after costs drop or prices increase. Alternatively, firms may invest in mediocre or negative return projects to gain knowledge and experience improving production efficiency. In this case, the spared high-performance projects can serve as insurance against a decrease in prices or as collateral.

Such trade-offs arise in various industries in which investment is essential for companies to sustain a competitive advantage, financial performance, and value (Mizik & Jacobson, 2003). The emergence and continuous growth despite price drops of the U.S. unconventional oil and natural gas industry is attributed to a balance in portfolio of projects with some investments focused on profitability of resource extraction and others aimed at productivity and therewith, production potential expansion (Ikonnikova et al., 2018). Regulatory uncertainty and new policies cause power companies to change their portfolios divesting from profitable assets, which however may not be used in the future, and investing in publicly preferred renewable and alternative technologies with much lower productivity and profitability. The latter is subject to a wide range of regulatory and price uncertainties (Reinartz & Schmid, 2016). Automotive firms manage their product portfolios, focusing on financial value, market potential, and various resource constraints. Differences in views on carbon-policy-related risks and the trajectory for technological efficiency of new technologies, such as electric battery and fuel cell or other hybrids, lead to divergence in production decisions (Gnann et al., 2018). The COVID-19 situation highlighted the challenges in front of pharmaceutical companies facing policy regulations and agility problems when balancing their R&D investment intensity, weighting productivity and competitiveness against financial risks (Giaccottoet et al., 2005; Pammolli et al., 2011). Empirical studies have confirmed the importance of financing considerations (Denis & Sibilkov, 2010; Bolton et al., 2014); production flexibility (MacKay, 2003; Reinartz & Schmid, 2016); demand and price uncertainty (Fuss & Vermeulen, 2008); and regulatory and technological uncertainty (Miao, 2005; Kang et al., 2014). Yet, the focus on individual factors rather than a combination and interplay of determinants has resulted in divergent insights, highlighting the need for a unified approach to support firms in their decision-making embracing a variety of investment factors and drivers (Benaija & Kjiri, 2014; CDP, 2019; Campiglio & Jagow, 2019).

The contribution of our work is twofold: 1) we develop a model to study the interplay of productivity and profitability affecting factors and their impact on investments and 2) we derive and analyse the relationship between investment drivers and the price elasticity of supply. Our analysis helps narrow the gap between investment theory and industrial economics, explaining distinctions in empirical evidence and theoretical insights. The presented model setup allows for a variety of investment drivers, but our primary focus is on the roles of 1) financial deficit and project investment or production capacity constraint, 2) firm's expectations on technology and price, and 3) the ability to improve productivity by investing. Motivated by empirical evidence from the largest unconventional natural gas resource in the U.S., Marcellus play, and inspired by the question of "will we ever stop using fossil fuels?"[4], we develop a framework capturing real-world firms' behaviour and helping explain why firms may forego investments in apparently profitable projects and instead invest in projects with the negative expected return, e.g., divesting from fossil fuels and investing in hydrogen.

To tackle the questions of project selection, allocation of capital, and corresponding production dynamics, we combine the elements of investment theory and project portfolio selection models, highlighting the role of revenue uncertainty, time delay, and project competition for firm's financial resources (He & Pindyck, 1992; Dixit & Pindyck, 1994; Archer & Ghasemzadeh, 1999). We consider a firm selecting projects and deciding how much to invest in each. The projects differ in their productivity, which increases with investing, and their ability to generate profit, which depends on the breakeven costs. The projects have finite production or investment potential and hence, investing and increasing production capabilities the firm exhausts its project options. We reveal how exhaustion, apart from the financial deficit argument presented in other studies on the subject, and the intensity of exogenous versus endogenous technological improvements helps explain investment dynamics and productivity growth (Jin et al., 2019; Levine & Warusawitharana, 2019). For instance, a limited number of production locations would explain the lack of investments in renewable generation in certain locations better than the financing argument. On the other hand, the George Mitchell's belief that the ability to improve unconventional resource recovery – known to be an abundant energy resource with potentially vast production capacity – could explain Mitchell's investments in the at-the-time highly unattractive Barnett shale play.[5] Analogously, our model would agree with the strategy of companies like BP investing in negative-return hydrogen projects and divesting from fossil energy. Financial justifications are weak in such a case, instead it is increasing carbon prices and steep learning curve expectations that drive such a transition.

Productivity growth and the corresponding production potential are intermingled with financial capabilities both of which are known to affect supply capabilities. Industrial and microeconomics provide a wide variety of models on the subject, yet, the effect of finances on supply responsiveness to price is rarely addressed in such a context (Caballero & Pindyck, 1992; Gomes, 2001; Miao, 2005; Beviá et al., 2015; 2020). Our analysis adds to the body of works exploring the interplay between investment strategy and supply by deriving the elasticity of supply as a function of the factors determining investments with price and technology expectations parameters. We can examine how productivity improvements and the financial performance affect the elasticity suggesting its changes over time as the resource base or set of technologies available alters. Thus, we foresee that the introduction of renewable

[4] Formulated by Covert et al., (2016) in their qualitative analysis of energy transition and factors affecting it.
[5] The lack of belief in the commercial potential of the resource made it hard for G. Mitchell to raise external capital; he took out two mortgages on his house to finance his original tests on horizontal drilling and hydraulic fracturing. Apart from the resource size, the founder of the unconventional resource industry, George Mitchell, was driven by the increasing natural gas prices and price increase expectations owing to the growing U.S. liquified natural gas imports.

or electric vehicle technologies shall affect the elasticity of supply *ceteris paribus* in the power sector and automotive industry, respectively. Similarly, a demand shock e.g. due to the COVID, would harm individual firms' and the entire industry's financial performance reducing the ability to respond to the following exogenous price changes, i.e. the elasticity of supply value would change.

Exploring the price elasticity of supply, we highlight the role of 1) financial deficit, 2) limitations in investment options, and 3) future price and technology expectations. We aim to derive the elasticity as a function of the listed factors explicitly, allowing for empirical verification. In this context, our study relates to the extensive literature on the production of non-renewable resources, started by Hotelling (1931), and works on the supply elasticity. Previous studies focused on exhaustion pay little attention to the endogeneity of productivity and financial constraints (Gaudet et al., 2001; Chakravorty et al., 2006; Chakravorty et al., 2008; Kellogg, 2011). In contrast, elasticity analyses emphasize the role of prices, established (rather than possible) production capacities, industry concentration, and technological advances missing variables reflecting exhaustion (e.g. Dahl, 1993; Dahl and Duggan, 1996; Krichene, 2002; Medlock, 2012; Ponce & Neumann, 2014; Newell, Prest, & Vissing, 2016; Hausman & Kellogg 2015). Smith & Lee (2017) reported the non-trivial link between resource exhaustion, productivity dynamics, and the price elasticity of supply. In their analysis of the U.S. unconventional resource supply, they suggested how cost savings may outweigh the lost revenue leading to a "backward bending" supply curve and pointed out that the differences in well productivity are fundamental for understanding the elasticity of supply. Following a similar line of reasoning, we expand their work and arguments presented by Mason & Roberts (2018) by considering investment capital deficit and intertemporal trade-off. We focus on differences between today's vs. tomorrow's return on investment driven by price and productivity changes. We consider firms investing in low-productivity low- or negative-return projects in order to expand future production capabilities and to improve cost-efficiency of the potential projects. Firms are prone to make such investments, temporarily decreasing its supply in times of increasing price expectations, hoping the loss in profit is mitigated and short-lived. In doing so, firms may enhance their ability to handle future price shocks and improve longevity.

Hence, understanding the supply consequences of investment decisions is critical for firms' resiliency and is essential for policy-makers and regulators to develop positive the energy transition incentives (Ilyina & Samaniego, 2012; Beviá et al., 2015, 2020; IEA 2019a,b; IHS, 2019; IEA, 2020). The presented model attempts to disentangle the trade-offs faced by a real-world firm and presents an expandable framework for addressing new emerging issues and challenges, such as those associated with environmental, social, and governance (ESG) calling for comprehensive evaluations of firm's strategies (Sundaram & Inkpen, 2004; Armstrong & Huck, 2010; Grim & Berkowitz, 2020). Under the pressure of public preferences or regulations, investors are prone to deviate from their main-stream goals and to re-evaluate investment projects by adjusting costs, benefits and discounting for carbon or socio-economic impacts (Hellweg et al., 2003; Reeder & Colantonio, 2013; Vivian & Maurel, 2019). In this regard, our goal is to provide a tool equally useful to industry, government, and the public for modelling firms' and industry behavior and its supply outcome and for projecting the responses to expected or sudden changes in market and regulatory environments.

We see another contribution in the presented analysis in narrowing the gap between investment strategy studies and industrial economics supply and producer models. The presented data justify our model complexity and the research agenda. We aimed at both developing the intuition and formulating testable hypotheses useful in empirical studies. We believe the results of our analysis are valuable to the industry and government practitioners suggesting which factors to consider in their decisions, what market reaction to expect (and why they may differ) emphasizing the role of technology and price expectations. Changes in regulations, public preferences, and market environment brining the following questions: shall a firm invest in low-carbon technologies now or wait; which technologies to invest first; what is the optimal allocation of financial funds and input resources given the perceived risks and future expectations? The list of factors crucial for investment decisions is growing calling for expandable and updatable evaluation frameworks, which would account for interactions in the relevant factors (CDP, 2019).

The rest of the paper is organized as follows. We start by presenting a motivating example listing the key observations which we will try to explain in the following sections. In section 3 we set up an investment model and discuss the key assumptions and model parameters. Then, we solve the model and examine what and how affects investment choices, paying special attention to projects with negative return, which we associate with novel technologies. In section 4, we use investment results to derive the elasticity of supply. We distinguish the reaction to current vs. future price changes. We conclude with implications and limitations of the model and its results.

2. Motivating Example

In 2018, an interdisciplinary team at the Bureau of Economic Geology, the University of Texas at Austin, published a data-driven study of U.S. unconventional natural gas resource development (Ikonnikova et al., 2018).[6] Using IHS well-level data combined with geologic resource characterizations and well-cost data, the researchers examined production location choices, investment trends, and the corresponding supply dynamics.

The study concluded with several essential observations referenced in our analysis. First, the drilling budgets have been correlated to the natural gas prices (Fig. 1, left plot). Aggregate play production had no apparent relationship to price. Instead, the supply from new wells drilled and completed within a given year – incremental production – was correlated to price changes. Using financial performance estimates for the individual well projects, the study established that investments appear to be a function of the previous year financial results and the expected future price.[7] The data analysis has also suggested that capital expenses on new wells, together with their supply, depend on the absolute price value, with the parameters of the relationship changing over time. The result was associated with the play maturity. The maturity implies the need to pay dividends and to compete with other resources or industries for capital, e.g., the Permian basin. As a result, the elasticity tends to decrease over time.

[6] The research was funded by a grant by from the U.S. Department of Energy and supported by IHS MarkIt data generously provided free of charge to the researchers at the Bureau of Economic Geology. For further details on the geologic and economic data and analyses, please see the original report (Ikonnikova et al., 2018).
[7] Similar findings have been reported in other shale play studies, e.g. Gulen et al. (2015) and Browning et al. (2013).

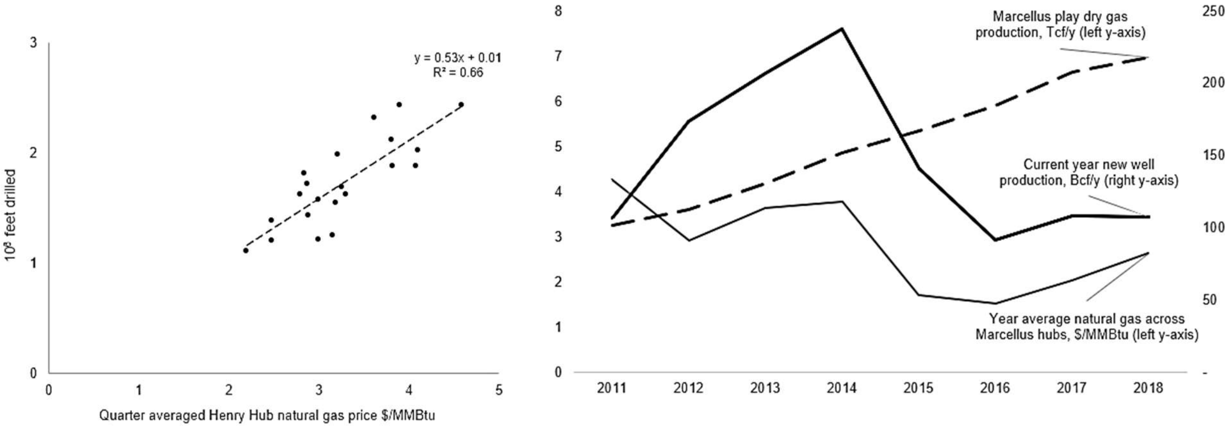
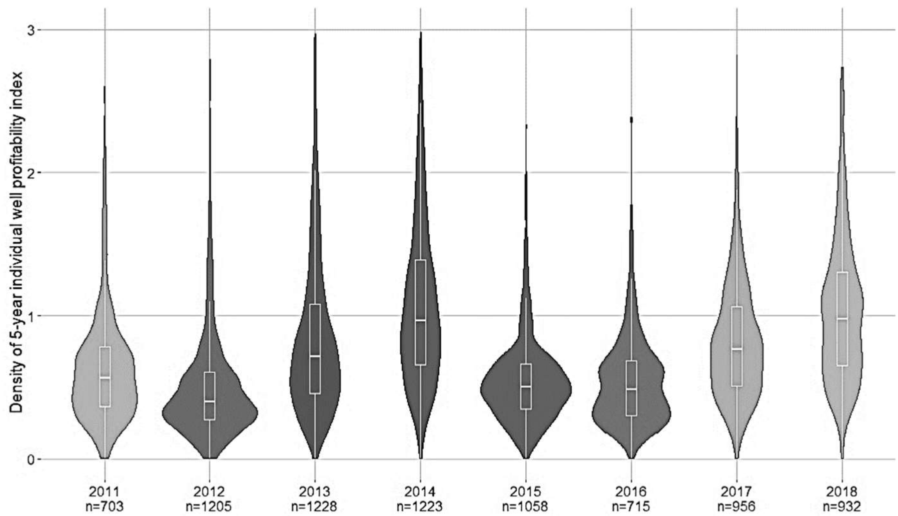


***Figure 1**.*
Natural gas price versus capital spending, approximated by feet drilled (left) and production (right).

The second set of observations concerns the choice of the drilling locations, or well projects. In contrast to the classical investment theory, the projects with negative expected present value, or a profitability index[8] smaller than 1, were systematically chosen for the drilling portfolio (Fig, 2a).

a)



[8] The profitability index is calculated as a ratio of the discounted future profits and the investment capital costs, thus measuring a project's ability to breakeven after a given number of years. In the presented statistics, the price used in the profit estimates is taken to be fixed and equal to the drill-year average.

b)

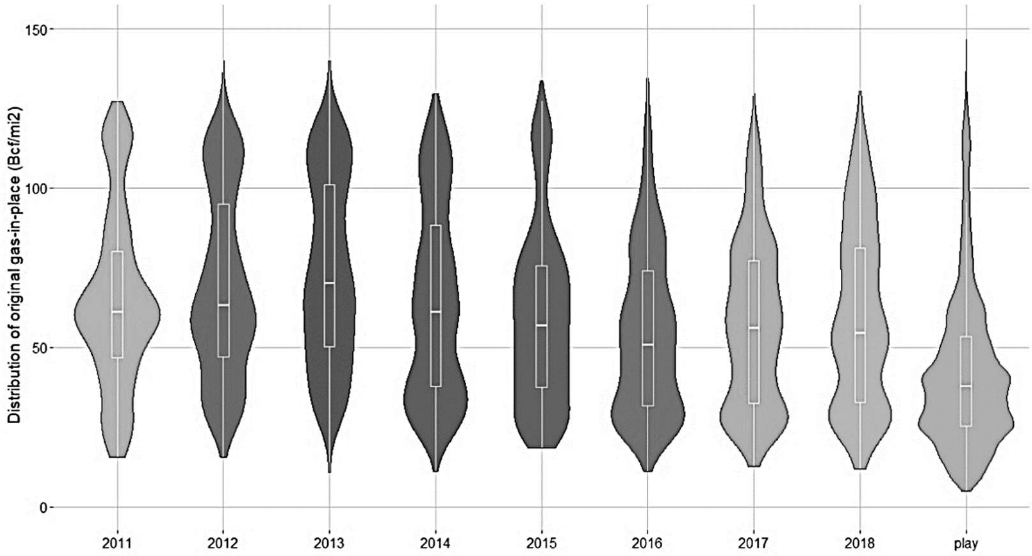


Figure 2*.*
Violin distribution plots for (a) 5-year profitability index of horizontal Marcellus gas wells and (b) original gas-in-place of the drilled locations and the entire play (based on Ikonnikova et al., 2018).

The average Marcellus well produces >65% of its expected ultimate recovery in the first 5 years; hence, wells with a profitability index of <0.65 are unlikely to breakeven within 20 years under the fixed price assumption (Male et al., 2016). This observation led to the following conclusions: 1) producers are likely to make their investment decisions based on the future price expectations (including hedging-based), and 2) a certain fraction of wells plays serves R&D purposes aimed at improving the productivity of similar wells in the future. The latter view was underpinned by the fact that even an optimistic increase in the future price would not allow 15-25% of wells to break even.[9] However, the median well seems to breakeven based on the short-term natural gas price outlooks in a corresponding year. Thus, in 2015-2016 natural gas prices plummeted across all Marcellus play hubs, resulting in a downshift of the corresponding profitability distributions (Fig. 2a). The simple formula of profitability index, with the profits proportional to the prices, allows for the following estimations: the median well with the profitability of ~0.55 in 2016 and the 2016 Marcellus average natural gas price of $1.53/MMBtu would need the 5-year average price to be $2.62/MMBtu to break even. By 2018, the year-average natural gas price in the Marcellus reached $2.63/MMBtu, suggesting producers' expectations are likely to be met.[10] Similar observations and accompanying conclusions have also been presented for the Haynesville and Eagle Ford plays (Gulen et al., 2015; Ikonnikova et al., 2017). The finding of variability in project returns was also highlighted by IEA (2019c) in aggregate for the oil and gas industry.

[9] The "optimistic" price projection refers to the EIA's Annual Energy Outlook scenarios in the corresponding years.
[10] The presented analysis includes the data on natural gas wells only, disregarding oil wells drilled in the north-western part of the Marcellus play, to limit the influence of oil prices on the analyzed drilling dynamics.

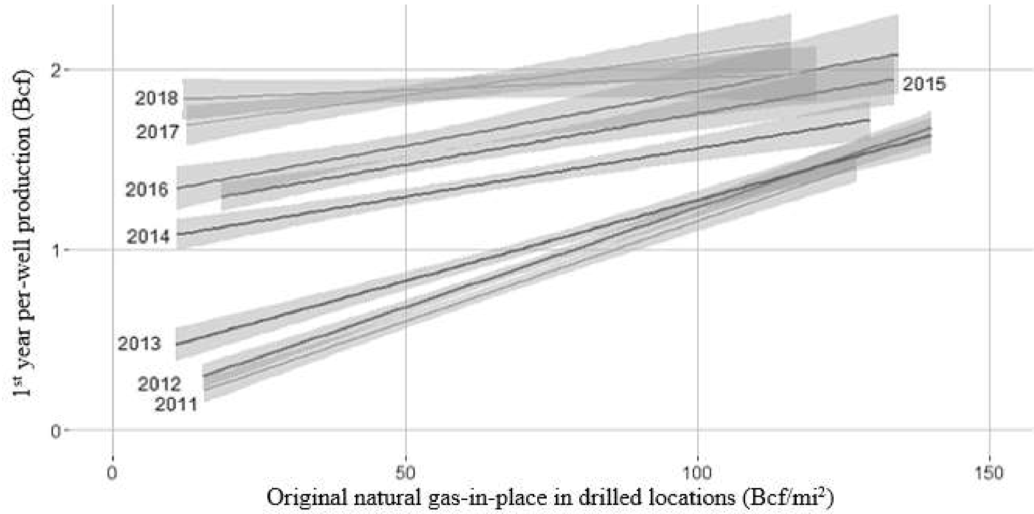


Figure 3.
Trend lines with 95% confidence intervals (shadowed) for the changes in per-well first-year natural gas production.

The third finding relevant for our study concerns the productivity and availability of investment options. Associating each well location with the original resource-in-place estimate, we can assign it the ultimate possible recovery or capacity and track the changes in productivity and location availability (Figs. 2b and 3). The Marcellus data reveal that both per-well and per 1000 feet of lateral length production of natural gas have increased over time. However, locations with higher initial productivity in high-resource-density areas exhibited lower improvements (Table 1). It has long been recognized that technological progress of resource recovery in high-density resource locations has less room for improvement and often less economic incentives to occur (Fisher et al., 1988). Productivity increases over time with experience, learning, and deployment of more suitable equipment. The data analysis suggests a weak link between investment intensity and recovery improvement, differentiating between industry-wide advances and firm-specific learning in line with evidence for conventional resource production (Kellogg, 2011).

Table 1. *Changes in the median Marcellus well first-year production per 1000 feet of lateral length productivity by geologic tier, % improvement relative to 2011.*

Location OGIP percentile	2012	2013	2014	2015	2016	2017	2018
Bottom 20%	4%	42%	94%	84%	119%	133%	178%
20 - 40%	2%	48%	94%	93%	147%	181%	136%
40 - 60%	9%	37%	71%	86%	147%	121%	137%
60 - 80%	22%	4%	3%	63%	78%	63%	114%
Top 20 %	0%	7%	57%	49%	67%	66%	65%

Whereas development intensity may increase productivity, it accelerates exhaustion of resource or investment potential. Looking at the distributions of well locations and the play-wide resource distribution, we find that high-resource-density locations are relatively scarce, yet are the most drilled in the early life of the play as the most commercially attractive (Fig. 2b). Over time, however, producers transition to investing in lower-resource-density locations, tapping into more abundant but initially unattractive projects in order to boost their productivity and make them profitable in the future. Aligning price and location choice statistics, we find that investments in production efficiency and expansion of the project portfolio prevail in times of higher prices or increasing price expectations. In 2013-2014, almost 30% of developed locations were low productivity ones, compared to 2015, when only half as much capital was dedicated to lower-resource-density locations. As a result, productivity in the low-density areas shifted upwards in 2014 and in 2017, the year when the prices recovered, and futures suggested further increases.

***Table 2**. The elasticity of Marcellus production and the cash elasticity of annual investments in drilling.*

	Marcellus NG price ($/MMBtu)	***Elasticity of Total Production***	***Elasticity of New-well Supply***	***Cash Elasticity of Investment***
2011	4.27			
2012	2.91	-0.27	-1.25	0.52
2013	3.63	0.68	0.81	0.31
2014	3.78	3.69	3.38	0.57
2015	1.71	-0.13	0.68	1.05
2016	1.53	-0.86	3.71	1.64
2017	2.03	0.41	0.58	2.15
2018	2.63	0.19	-0.10	0.55

Combining financial estimates with historical price dynamics and distinguishing between the legacy (existing by the beginning of a new year) and incremental new-well production, we present the evidence of negative price elasticity of supply (Table 2). We note that the negative elasticity of the entire play production is associated with all negative price changes. In other words, the decrease in natural gas prices had no negative effect on Marcellus production. Yet, looking at the new-well supply, we find that the elasticity is negative in the play's early life and in the last year. That suggests that positive expectations (e.g., technologic efficiency improvement) may outweigh the price signals in the growth stage. In contrast, in late life, the negative elasticity is likely to be explained by debt buy-outs and the necessity to pay dividends, reducing the fund available for reinvestment. In line with the first discussed observation, we find that the cash flow elasticity of investments is positive.

The evidence of energy companies investing in seemingly uneconomic projects, leading to the negative elasticity of supply, is not limited to the unconventional industry. Energy companies worldwide, and especially in Europe, increase the share of new technologies in their portfolios, many of which, like hydrogen, are not yet proven to be economically viable (Chapman et al., 2020). Recognizing a variety of explanations and rationales for such investment strategy, including behavioral finance, security of supply, and reputation-related arguments, in the further presented analysis, we focus on the trade-off between production and financial capabilities and the effects of price and technological expectations. Our goal is to explain: why and when producers are prone to invest in projects with negative return forgoing high-return alternatives and how such investment behavior determines the supply dynamics, namely, the negative elasticity phenomenon.

In the next section, we proceed to the formal analysis of investments. We examine how a firm (or an industry represented by a set of firms) considering a set of investment options chooses in which projects and how much to invest. Projects differ in productivity, profitability, and ultimate production potential. By investing, a firm may improve productivity, but it may not have sufficient funds to invest optimally, i.e. may face a financial deficit. Understanding firms' investment behavior is critical to explain the elasticity variability.

3. Firm Value Model

We consider a rational risk-neutral firm[11], with production small enough to affect the market prices or price expectations.[12] At the beginning of each period, the firm invests in production to maximize its value V_t. Following the classical Modigliani-Miller definition, the value is given by the cash profit Π_t and the present value of assets, A_t:

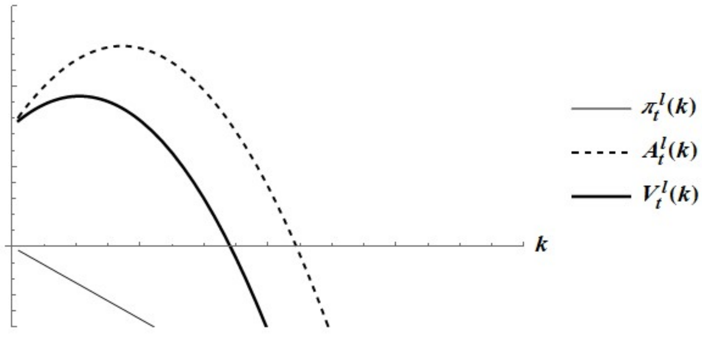
$$V_t = \Pi_t + A_t \Rightarrow max \tag{1}$$

The profit is defined by the production from the realized projects $l \in L$ and the *net* price $p_t^l = p_t - c_t^{l^{be}}$ equal to the difference between the breakeven cost and the market price. Thus, the profit is similar to the accounting return on investment. Projects differ in productivity or production per unit of cost q_t^l, which affect the net price value distribution. Together with the capital invested, k_t^l, productivity determines the output from a given project: $\bar{Q}_t^l \leq q_t^l k_t^l$, constrained by the project option's total production *capability.* We rewrite the capacity constraint as the investment constraint: $\bar{K}_t^l \geq k_t^l$ defining the remaining investment potential for each l. Then, the total profit is given as:

$$\Pi_t = \sum_{l \in L} \pi_t^l = \sum_{l \in L} p_t^l q_t^l k_t^l \tag{2}$$

In the context of the Marcellus example, well productivity, measured in cubic feet of natural gas per unit of lateral length, determines the expected well recovery $q_t^l k_t^l$ as a function of the well length and completion intensity or well cost k_t^l. Similarly, one can calculate the productivity of a windmill placed in a given location. While generated energy depends on the installed turbine capacity, it is also limited by the wind speed pattern just like the fossil energy production is constrained by the original resource-in-place.

Important to note that net price can be negative, for instance, in the case of a novel technology with low production efficiency. Thus, the profit function can take negative values but only if investments are expected to increase the asset's value compensating for the financial loss, as depicted in Figure 4. We assume that assets with both profit and asset value negative are not included into the total value function.



[11] The assumption of risk neutrality does not limit the generality of our analysis but helps keep the analysis straightforward. Alternatively, a corresponding correction of the discounting and risk factors could be applied.
[12] In the case of an industry analysis, one can assume that prices are set by the global markets and the considered industry is relatively small to affect the world price equilibrium.

Figure 4.

The firm's growth assets, profit and value when the current net price of the location is negative, whereas the future net price is positive.

Hence some project may bring a greater profit whereas others promise an increase in the asset value. Focusing on the latter, we define the remaining production potential as $\bar{Q}_{t+1}^{l} = \left(\bar{Q}_{t}^{l} - q_{t}^{l}k_{t}^{l}\right) \cdot \tau_{t}^{l}$ and allow for its increase, $\bar{Q}_{t+1}^{l} \geq \bar{Q}_{t}^{l}$, if technology multiplier τ is large enough. Then, we express the value of assets:

$$A_t = \sum_{l \in L} \gamma_t^l p_{t+1}^l \bar{Q}_{t+1}^l = \sum_{l \in L} \gamma_t^l p_{t+1}^l \cdot \left(\bar{Q}_t^l - q_t^l k_t^l\right) \cdot \tau_t^l \tag{3}$$

where p_{t+1}^{l} reflects future price expectations and project-specific parameter γ captures various regulatory uncertainties and other idiosyncratic risks[13]. As mentioned earlier, we assume the firm accounts only for assets with the positive future net price not including assessing A_t. To save on notations, we use $\hat{p}_{t+1}^{l} = \gamma^{l} p_{t+1}^{l}$ unless discussing γ specifically. One may notice that such a definition of the asset value accounts for the liquidation or the salvage value.

To complete the setup of the firm's value maximization problem, we introduce the investment budget constraint and assumptions on the price expectations. Based on the presented evidence and the insights from other studies, like Ross et al. (1993), we consider a firm relying primarily on its internal funds to finance investments with $\sum_{l \in L} k_t^l \leq \varepsilon_t \cdot \Pi_{t-1}$, where ε_t is some leverage parameter. The leverage refers to the ability and willingness to borrow capital. In general, it depends on various factors, including the value of assets, but we assume it exogenous and focusing on its effect on one-period decisions, drop the subscript. Instead, we emphasize that financing depends on the past price with $\Pi_{t-1} \sim f(p_{t-1})$; hence, investments are price history dependent.

Furthermore, we assume that the firm is fairly certain of current price p_t, e.g., thanks to hedging, but holds expectations about future price p_{t+1}^{e} which may not realize. We distinguishing between p_{t+1}^{e} at time t and "fairly certain" p_{t+1} at t+1 defining the future net price as $p_{t+1}^{l} = p_{t+1}^{e} - c_{t+1}^{lbe}$. Hence, while a change in current price translates into the present net price directly $\frac{dp_t^l}{dp_t} = 1$, the change in the future net price expectations $\frac{d\hat{p}_{t+1}^l}{dp_{t+1}^e} = \gamma$ depends on the associated risks and uncertainties. When risks are extremely high $\gamma \rightarrow 0$, the firm relies on the current profitability evaluation neglecting the value of A_t^l. On the other hand, the decrease in uncertainty as $\gamma \rightarrow 1$ would make price expectations increasingly important in the decision-making.

Hence, we define the investment problem and the timeline of decisions with (4), (5), and Figure 5:

$$V_t = \sum_{l \in L} p_t^l q_t^l k_t^l + \sum_{l \in L} \hat{p}_{t+1}^l \left(\bar{Q}_t^l - q_t^l k_t^l\right) \cdot \tau_t^l \xrightarrow[\{k_t^l\}_{l \in L}]{} max \tag{4}$$

$$\text{BC:} \quad \varepsilon_t \cdot \Pi_{t-1} - \textstyle\sum_{l \in L} k_t^l \geq 0 \qquad \text{and} \qquad \text{CC:} \quad \bar{K}_t^l - k_t^l \geq 0 \tag{5}$$

[13] Idiosyncratic, or unsystematic risks as compared to systematic risks captured by the discounting factor used in breakeven cost calculations, can be neglected with $\gamma = 1$ or added with $\gamma < 1$, e.g. to differentiate fossil versus other energy projects not subject to the carbon regulations risks.

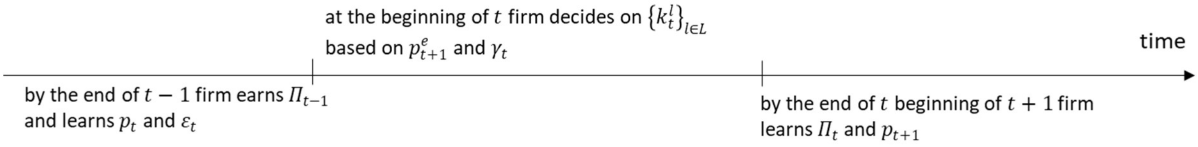


Figure 5.
The timeline of firm's decisions.

Before we proceed with the solution for the optimal investments, we examine the role of technology parameters and offer some intuition about them. In the next section, we use the results to derive and study the elasticity of supply.

3.1 Production Potential and Technology Expectations

At the beginning of each period, the firm decides which projects $l \in L$ to develop and at what capacity, balancing between value creation and value appropriation. The investment decision affects production and investment potential available in the next period: investing increases productivity or cost efficiency, while exhausting production and investment potential. The essential role in the resolution of this trade-off play technology expectations. We define τ as a linear function of investment: $\tau = \alpha + \beta \cdot k$ and express the remaining production potential, used to assess A_t^l, as:

$$\bar{Q}_{t+1}^l = \left(\bar{Q}_t^l - q_t^l k_t^l\right) \cdot \left(\alpha_t^l + \beta_t^l k_t^l\right) = \bar{Q}_0^l \prod_{T=1}^{t} (\alpha_t^l + \beta_t^l k_T^l) - \sum_{\theta=1}^{t} q_\theta^l k_\theta^l \prod_{T=\theta}^{t} (\alpha_t^l + \beta_t^l k_T^l) \tag{6}$$

Expression (6) implies that production growth could accelerate technological progress and thus, slow down the depletion. Formally speaking, technology may affect q_t^l by improving productivity or reducing production costs and $\bar{K}$ increasing potential. The latter describes the situation of new resource or technology discovery. The distinction is especially important as it may affect the sensitivity to capital costs. Yet, we leave that analysis for future research. Although we do not address the addition of new projects explicitly, our framework allows for $L_t \subset L_{t+1}$ expansion. Alternatively, one can consider L including all the possible project options, not invented or discovered yet, with corresponding $q_t^l \to 0$.

We suggest interpretation of the introduced technology parameters to facilitate the tractability of the following results. Thus, we consider β reflects firm's internal ability to learn from experience. Then, the firm may draw its expectations on its value from the past activity or some internal knowledge. A firm focused on its internal innovation and technological improvements with $\beta > 0$ and $\alpha \to 1$, the growth in the remaining potential is determined by:

$$\bar{Q}_{t+1}^l = \left(\bar{Q}_t^l - q_t^l k_t^l\right) \cdot (1 + \beta_t^l k_t^l) \tag{7}$$

$$\bar{Q}_{t+1}^l \geq \bar{Q}_t^l \quad \Leftrightarrow \quad \beta_t^l \geq \frac{1}{K_t^l - k_t^l} \tag{8}$$

Inequality (8) defines the learning threshold level required to prevent the capacity from shrinking, given $\bar{Q}_t^l = \overline{K}_t^l \cdot q_t^l$. The technological progress can help balance the exhaustion and keep the asset value from decline under the fixed price assumption, with β dependent on ($\overline{K}_t^l$ - k_t^l) or the exhaustion rate: the higher production rate should be accompanied by more aggressive learning to prevent or slow down the exhaustion. However, the closer the exhaustion of a given project or the smaller the investment potential is, the harder it is to compensate the shrinkage with technology: $\beta_t^l \in (\infty, \frac{1}{\bar{K}_t^l})$ while $k_t^l \in (0, \bar{K}_t^l)$.

The evidence presented in the Marcellus example and in Kellogg (2011) lets us assume that information dissemination and knowledge transfer result in technology spill-over effects, captured by $\alpha_t^l > 1$ independent of k_t^l. We explore the role of technologic parameters plotting $\bar{Q}_{t+1}^l$ as a function of investment assuming some fixed q_t^l and $\bar{K}_t^l$ (Fig. 6).

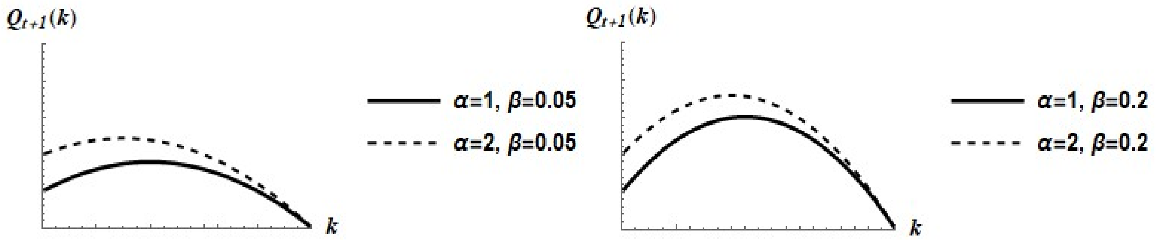


Figure 6.
Production potential as a function of investments and technological improvement parameters.

Since $\bar{Q}_{t+1}^l(k_t^l)$ is the second-degree polynomial, depicted by the opening downward parabola, reveals that production or investment potential may increase as well as decrease in k_t^l. Thus, intensive development would exhaust the project potential irrevocably with $\bar{Q}_{t+1}^l(k_t^l \to \bar{K}_t^l) \to 0$. Yet, at The better the internal learning ability is, the higher the potential increase could be achieved. Yet, at $k \leq k^* = \frac{\bar{K}}{2} - \frac{\alpha}{2\beta}$ the potential increases. Moreover, thanks to the spill-over effect the potential can grow even without investments. Note that external progress makes own learning less valuable, with the potential maximizing investments being smaller at greater α.

The difference in learning abilities or α and β expectations helps explain the variance in investments across firms which otherwise face similar investment problem. Non-innovative firms with $\beta \sim 0$ would prefer to free-ride on α, whereas innovative firms with high β would invest $k^* > 0$. However innovative, the firms would gradually lose interest in learning as project matures or gets exhausted and $\bar{K} \to \frac{\alpha}{\beta}$. A firm has little benefit from learning when its remaining inventory is small. With this intuition, we proceed with the solution of the investment problem.

3.2 Investment Problem

We have established that making investment decisions, the firm balances the increase in its value through profit and assets' value. The former defines firm's financial capabilities, since Π_t enters the next period budget, whereas the latter determines the future production capabilities $\{\bar{Q}_{t+1}^l\}_{l \in L}$. Hence, the value maximization problem represents a trade-off between the value creation and extraction. Firm's choice is based on expectations regarding technological progress, given by $\alpha \geq 1$ and $\beta \geq 0$, and price and other risk expectations captured by $\hat{p}_{t+1}^l$.

We start our analysis by revealing the non-trivial nature of the trade-off (Fig. 7). Consider a firm with two projects: low and $high$ with $q^{low} < q^{hig}$. With Marcellus example in mind, assume productivity of can hardly change with $\beta^{high} \to 0$, whereas β^{low} is high so that $\bar{Q}_{t+1}^{low}$ can grow.

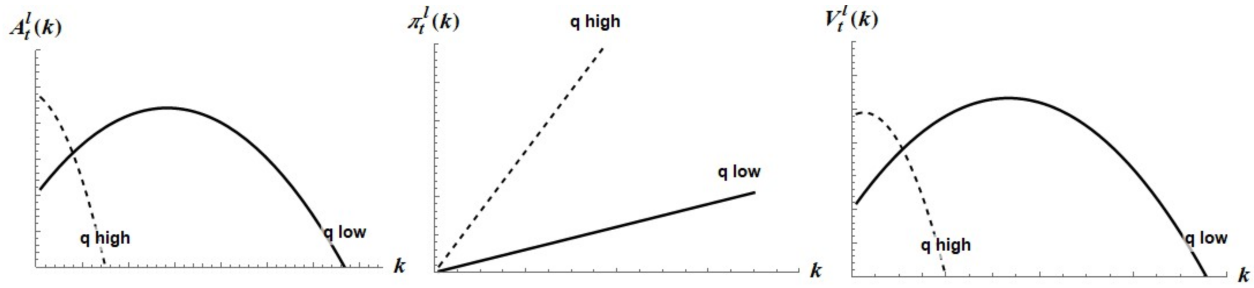


Figure 7.
The differences in the asset value, profit, and the total value of a low versus high productivity projects.

Figure 7 shows how A_t^{high} can only be exhausted and hence, is a monotonically decreasing function of investment, whereas A_t^{low} is a downward opening parabola with the maximum at $k_t^{low} > 0$. Clearly, the financial performance of the high-productivity project is better for the same level of investment, as illustrated by Π_t^l plot. As a result, the total firm value is a parabola for both projects, but the development of low project results in a higher firm value, would only one project be developed.

However, had the firm be financially constrained, it may prefer the high productivity project, be indifferent between the two or choose the low one. Thus, our framework provides 1) the rationale for firms to prefer low-productivity projects over the high-return project or even to choose projects with negative profit (Fig. 4) and 2) the explanation for firms with similar investment projects to make different decisions due to the financial constraints or differences in expectations.

Now we turn to the formal model solution. Rearranging (4) we rewrite the objective function as:

$$V_t = \sum_{l \in L} \left[\left(p_t^l - \alpha \hat{p}_{t+1}^l\right) q_t^l k_t^l - \alpha \hat{p}_{t+1}^l \bar{Q}_t^l + \beta \hat{p}_{t+1}^l \bar{Q}_t^l k_t^l - \beta \hat{p}_{t+1}^l q_t^l \left(k_t^l\right)^2 \right] \xrightarrow[\{k_t^l\}_{l \in L}]{} max \tag{9}$$

which is solved under the financing constraint $\sum_{l \in L} k_t^l \leq \varepsilon_t \cdot \Pi_{t-1}$ and capacity or investment potential constraint $k_t^l \leq \bar{K}_t^l$. We solve (9) using the Lagrangian and Kuhn-Tucker conditions:

$$L_t(\{k_t^l\}_{l \in L}, \{\lambda_t^l\}_{l \in L}, \mu_t) = V_t + \sum_{l \in L} \lambda_t^l \left(\bar{K}_t^l - k_t^l\right) + \mu_t(\varepsilon \cdot \Pi_{t-1} - \sum_{l \in L} k_t^l) \tag{10}$$

$$k_t^l \frac{\partial L_t}{\partial k_t^l} = 0 \text{ and } \frac{\partial L_t}{\partial k_t^l} \geq 0 \tag{10.1}$$

$$\lambda_t^l \frac{\partial L_t}{\partial \lambda_t^l} = 0 \text{ and } \frac{\partial L_t}{\partial \lambda_t^l} \geq 0 \tag{10.2}$$

$$\mu_t \frac{\partial L_t}{\partial \mu_t} = 0 \text{ and } \frac{\partial L_t}{\partial \mu_t} \geq 0 \tag{10.3}$$

To facilitate the interpretation, we distinguish three major cases with respect to the constraints:

Case I (*Unconstrained*): If the financial situation of the firm allows it to develop all the available project options optimally, so that the budget constraint is non-binding, we solve the reduced form Lagrangian with the third summand dropped.

Case II (*Budget Constrained*): When the budget constraint is such that none of the capacity constraints become effective: $\forall l$: $\bar{K}_t^l > \varepsilon_t \cdot \Pi_{t-1}$, we solve (10) dropping the second summand.

Case III (*Capacity Constrained*): When the constraints are such that $\exists l$: $\sum_{l \in L} \bar{K}_t^l > \varepsilon_t \cdot \Pi_{t-1} > \bar{K}_t^l$ we solve (10) with both constraints intact.

The solution of (10) determines the optimal investment portfolio $\{k_t^{l^*}\}_{l \in L}$ for the three listed cases: $k_t^{l^*} = k_t^{l^{UC}}$ – unconstrained when neither BC or CC is binding; $k_t^{l^*} = k_t^{l^{BC}}$ – only budget constraint matters; and $k_t^{l^*} = k_t^{l^{CC}}$ when both constraints are effective. We start with the unconstrained case and derive the other cases with the reference to it. We write down the first order condition for each link and saving on notations drop the indexes in the technology parameters:

$$\frac{\partial V_t}{\partial k_t^l} = 0 = \left(p_t^l - \alpha \hat{p}_{t+1}^l\right) q_t^l + \beta \hat{p}_{t+1}^l \bar{Q}_t^l - 2\beta \hat{p}_{t+1}^l q_t^l k_t^l$$
$$k_t^{l^{UC}} = \frac{p_t^l}{2\beta \hat{p}_{t+1}^l} - \frac{\alpha}{2\beta} + \frac{\bar{Q}_t^l}{2q_t^l} = \frac{(\rho_t^l - \alpha)}{2\beta} + \frac{\bar{K}_t^l}{2} \qquad (11)$$

We find that the optimal investment is a function of the project's intertemporal opportunity cost $\rho_t^l = \frac{p_t^l}{\hat{p}_{t+1}^l}$ measuring the trade-off between today's and tomorrow's production worth and highlighting the role of the future risk. If the net price remains fairly constant and risks are low, $\gamma \to 1$, then $\rho_t^l - \alpha \leq 0$ and investments increase in β. In contrast, when uncertainty and $\rho_t^l - \alpha$ turns positive, then investments is a decreasing function of β. The uncertainty destroys the value of learning and induce the firm to produce more today. Furthermore, low risk and high technological spill-over effect could lead to lower investments and "waiting" as a preferred strategy. As $\frac{(\rho_t^l - \alpha)}{\beta} \to 0$ investments are increasingly dependent on the potential, whereas under the lower ability to learn $\beta \to 0$ the more producers driven by the intertemporal opportunity cost. Apply the non-negativity condition $k_t^{l^{UC}} \geq 0$ implying $\rho_t^l \geq \alpha - \beta \bar{K}_t^l$, we find that in a mature industry with $\alpha \to 1$ and $\beta \to 0$, investments are primarily driven by $\rho_t^l \geq 1$ expectations.

Hence, we find that in combination with uncertainty, technology factors have ambiguous effect on investments. In contrast, disregard uncertainty and technology, the greater investment (and production or market) potential always translates into more intensive development. Comparing the results across the project options, we determine that ceteris paribus the firm would invest more in options with greater production potential or with the greater net price advantage. Our insights differ from those from the classical Hoteling resource extraction problem, which stipulated that resource producers are motivated by profit neglecting the role of asset value. The original model also ignored the role of technologic progress and risks, which could expand or shrink future production capabilities. That is why our results suggest that the closer the firm to the exhaustion of a given resource, the less it might invest in a given project. The second case, BC, will suggest that the firm would simply retarget its funds on projects with a higher potential, i.e. focusing on developing new projects. This conclusion explains why some resources plays, such as coal mines or the shale gas plays, are abandoned before completely exhausted.

We summarize the above results in:

Corollary 1 (Unconstrained Case): The firm shall

- *invest in any project with* $\frac{p_t^l}{\hat{p}_{t+1}^l} > \alpha$, *with* ${k_t^l}^{UC} = \frac{1}{2\beta}\left(\rho_t^l - \alpha\right) + \frac{\bar{K}_t^l}{2}$
- *forgo investments in* l *if* $\bar{K}_t^l < \frac{\alpha}{\beta} - \frac{\rho_t^l}{\beta}$ *or* $p_t^l - \hat{p}_{t+1}^l \leq 0$ *under* $\alpha = 1$ *and* $\beta = 0$.

We investigate the effect of key parameters on the optimal investments graphically in Figure 8. Our plots feature how the same investment level would require a higher current price or would allow for a lower future price (incl. risks) under the increasing technological spill-over effect. The ability to increase productivity through β could have positive as well as negative effect on optimal investments depending on the price expectations.

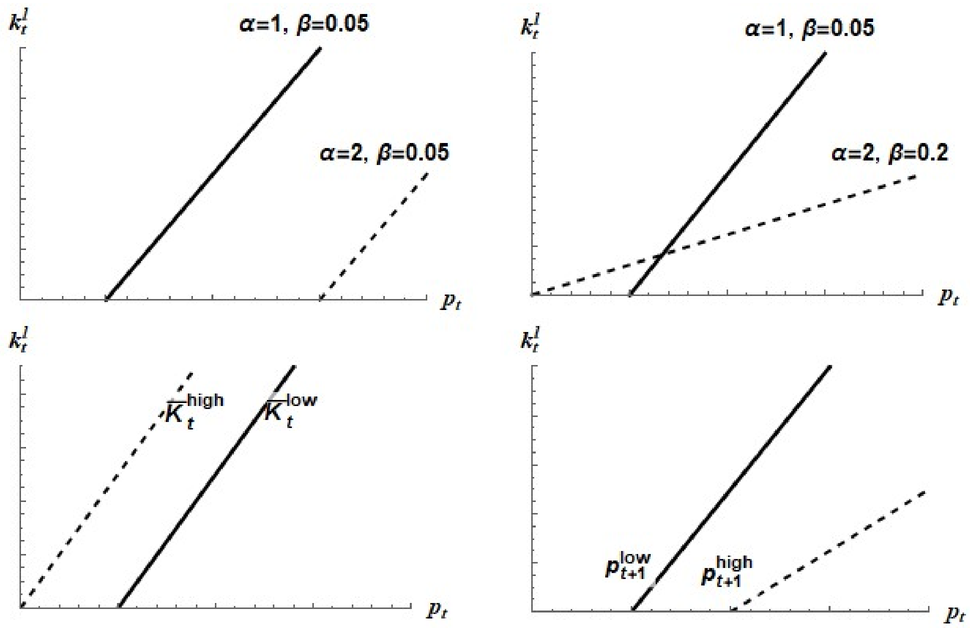


Figure 8.

The effect of technology, price expectations, and investment potential on $k_t^l = {k_t^l}^{UC}$ *with the thick black line characterizing the same set of parameters across all the plots.*

Figure 8 also demonstrates how the optimal investments may decrease while p_t^l and p_t remains the same or increases owing to the change in the future net price. Namely, if the firm expects its breakeven costs to fall thanks to technological improvements or if a positive price shock is expected, ${k_t^l}^{UC}$ will rise. This observation lays the foundation for the negative elasticity phenomenon explained in the next section.

Now we proceed with the budget-constrained firm with financial deficit defined as inability to invest optimally in all the project options: $\varepsilon_t \cdot \Pi_{t-1} < \sum_{l \in L} {k_t^l}^{UC}$. For any given financing multiplier ε_t, the deficit depends on the expected prices which drive the willingness to invest and the past realized profit. Hence, we suggest another rational for financial constraint other than capital cost. We recognize that one may use the expected profit and define the deficit. Our model allows for that too, e.g. one can set $\varepsilon_t(\Pi_t)$. Yet, we leave the solution of the investment recursion for further analysis treating here the financial leverage as given emphasizing the role of own funds, especially to finance low or negative return $p_t^l < 0$ projects.

The effective budget constraint defines the shadow cost of financing measured by the Lagrange multiplier: $\mu^* = \frac{\partial V_t}{\partial k_t^1} =..= \frac{\partial V_t}{\partial k_t^l} =..$ with incentives to invest equalized across the project options. We express investments in $m \in L/l$ through k_t^l and substitute the result into the budget constraint:

$$p_t^l q_t^l + \hat{p}_{t+1}^l\left(\beta \bar{Q}_t^l - \alpha q_t^l - 2\beta q_t^l k_t^l\right) = p_t^m q_t^m + \hat{p}_{t+1}^m(\beta \bar{Q}_t^m - \alpha q_t^m - 2\beta q_t^m k_t^m) \tag{12}$$

$$k_t^m = \frac{\left[p_t^m q_t^m + \hat{p}_{t+1}^m(\beta \bar{Q}_t^m - \alpha q_t^m) - p_t^l q_t^l - \hat{p}_{t+1}^l\left(\beta \bar{Q}_t^l - \alpha q_t^l - 2\beta q_t^l k_t^l\right)\right]}{2\beta \hat{p}_{t+1}^m q_t^m} \tag{13}$$

$$k_t^{l^*} = \varepsilon_t \cdot \Pi_{t-1} - \sum_{m \in L/l} \frac{\left[p_t^m q_t^m + \hat{p}_{t+1}^m(\beta \bar{Q}_t^m - \alpha q_t^m) - p_t^l q_t^l - \hat{p}_{t+1}^l\left(\beta \bar{Q}_t^l - \alpha q_t^l - 2\beta q_t^l k_t^{l^*}\right)\right]}{2\beta \hat{p}_{t+1}^m q_t^m} \tag{14}$$

with $\hat{\pi}_{t+1}^l = \hat{p}_{t+1}^l q_t^l$ representing the return on the one unit of future investment, we derive:

$$\begin{aligned} k_t^{l^*} = \varepsilon_t \cdot \Pi_{t-1} + \frac{1}{2\beta \prod_{m \in L \setminus l} \hat{\pi}_{t+1}^m} \sum_{m \in L \setminus l} \left(\left(\rho_t^l + \beta \bar{K}_t^l - \alpha\right) \prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i - 2\beta k_t^{l^*} \prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i \right) \\ - \sum_{m \in L \setminus l} \left(\frac{\rho_t^m}{2\beta} - \frac{\alpha}{2\beta} + \frac{\bar{K}_t^m}{2} \right) \end{aligned} \tag{15}$$

$$\begin{aligned} k_t^{l^*} = \frac{\varepsilon_t \cdot \Pi_{t-1} \cdot \prod_{m \in L \setminus l} \hat{\pi}_{t+1}^m}{\sum_{m \in L}\left(\prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i\right)} + \left(\rho_t^l + \beta \bar{K}_t^l - \alpha\right) \frac{\sum_{m \in L \setminus l} \prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i}{2\beta \sum_{m \in L}\left(\prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i\right)} \\ - \frac{\prod_{m \in L \setminus l} \hat{\pi}_{t+1}^m}{2\beta \sum_{m \in L}\left(\prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i\right)} \sum_{m \in L \setminus l} (\rho_t^m - \alpha + \beta \bar{K}_t^m) \end{aligned} \tag{16}$$

We simplify (16) by dividing and multiplying $\frac{\prod_{m \in L \setminus l} \pi_{t+1}^m}{\sum_{m \in L}\left(\prod_{i \in L \setminus m} \pi_{t+1}^i\right)}$ by $\prod_{m \in L} \pi_{t+1}^m$ and introducing:

$$\eta_{t+1}^l = \frac{\prod_{m \in L \setminus l} \hat{\pi}_{t+1}^m}{\sum_{m \in L}\left(\prod_{i \in L \setminus m} \hat{\pi}_{t+1}^i\right)} = \frac{\hat{\pi}_{t+1}^l}{\sum_{m \in L} \hat{\pi}_{t+1}^m} \tag{17}$$

Our interpretation of η_t^l build on the understanding of $\sum_{m \in L} \hat{\pi}_{t+1}^m$ as the worth of the all projects portfolio had one unit of capital $k = 1$ invested in each project tomorrow, or *future unit profitability*. Then, (17) measures individual project's contribution to this unit profitability*:* the greater option's weight is, the more the firm is compensated tomorrow for not investing today. Simplifying (16) using option's relative profitability weights, we derive:

$$k_t^{l^*} = \eta_{t+1}^l \cdot \varepsilon_t \cdot \Pi_{t-1} + \frac{1 - \eta_{t+1}^l}{2\beta}\left(\rho_t^l + \beta \bar{K}_t^l - \alpha\right) - \frac{\eta_{t+1}^l}{2\beta} \sum_{m \in L \setminus l} (\rho_t^m + \beta \bar{K}_t^m - \alpha) \tag{18}$$

$$k_t^{l^*} = \eta_{t+1}^l \cdot \varepsilon_t \cdot \Pi_{t-1} + \frac{1}{2\beta}\left(\rho_t^l + \beta \bar{K}_t^l - \alpha\right) - \frac{\eta_{t+1}^l}{2\beta} \sum_{m \in L} (\rho_t^m + \beta \bar{K}_t^m - \alpha) \tag{19}$$

$$k_t^{l^{BC}} = k_t^{l^{UC}} + \eta_{t+1}^l \cdot (\varepsilon_t \cdot \Pi_{t-1} - \sum_{m\in L} k_t^{m^{UC}}) \tag{20}$$

Since $\varepsilon_t \cdot \Pi_{t-1} - \sum_{m\in L} k_t^{m^{UC}} < 0$, expression (20) reveals that the financial deficit is distributed based on projects' weights: the higher relative profitability is expected tomorrow, the more the project is rationed today. Projects with the same expected return are rationed proportionally to their productivity: $\frac{\eta_{t+1}^l}{\eta_{t+1}^m} \to \frac{q_t^l}{q_t^m}$ for $\hat{p}_{t+1}^l \cong \hat{p}_{t+1}^m$. Besides, a higher relative price ρ_t^l would encourage investments, but the increasing *future unit profitability* of other projects $m \in L/l$ could "steal" investments reducing $k_t^{l^{BC}}$ and reallocating the funds to other options.

Corollary 2 (Budget Constrained): *A budget-constrained firm would allocate its funds:*

- *reducing investments relative to the optimum based on the project's future unit profitability:* $k_t^{l^{BC}} = k_t^{l^{UC}} + \eta_{t+1}^l \cdot \left(\varepsilon_t \cdot \Pi_{t-1} - \sum_{m\in L} k_t^{m^{UC}}\right)$.

Figure 9 helps to see the effect of financing deficit and project's weight in the future unit portfolio worth on the optimal investment $k_t^{l^{BC}}$. We draw the plot assuming all $\hat{p}_{t+1}^l \geq 0$, the negative net price would make the firm more impatient to invest reallocating the funds from other projects: $\eta_{t+1}^l(\hat{p}_{t+1}^l < 0) < 0$ and $k_t^{l^{BC}} \geq k_t^{l^{UC}}$. The plot emphasizes that the higher project's return in the future, the more it is rationed. For the fixed ε, the greater the net profit from the previous period is, the smaller the financing deficit is, comparing to the case when financing is ample.

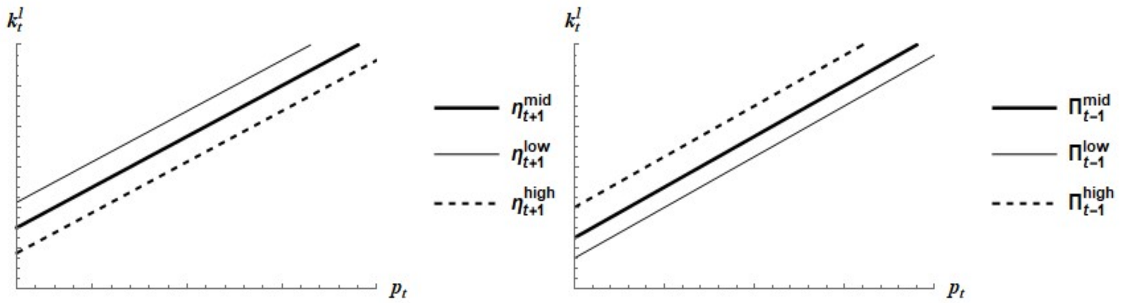


Figure 9.
The effect of the future projects' value on the investment budget allocation $k_t^l = k_t^{l^{BC}}$.

The plots also help us see how for the same or increasing price levels, the investments may fall due to 1) a change in a given option's future unit worth or 2) an increase in the total or other options' unit worth. Hence, one may expect a negative production change under increasing prices explained by the changes in the value of alternatives. While statistical models often capture that phenomenon with fixed or random effects, our model provide tangible intuition and suggest that such effects would vary over time.

Finally, we derive the solution for the third case by applying the capacity constraint $k_t^l \leq \overline{K}_t^l$ to the BC case result and formulate:

Corollary 3 (Fully Constrained): *The firm with insufficient investment budget and with the limited production potential invests* $k_t^{l^{CC}} = min\left[\overline{K}_t^l, k_t^{l^{UC}} + \eta_{t+1}^l \cdot \left(\varepsilon \cdot \Pi_{t-1} - \sum_{m\in L} min\left[\overline{K}_t^m, k_t^{m^{UC}}\right]\right)\right]$.

One can understand the distinction between CC and BC cases by realizing that options with active capacity constraints would "release" the capital reducing the effect of rationing for the other options. Hence, since the term $\sum_{m \in L} min[\bar{K}_t^m, k_t^{m^{UC}}] \leq \sum_{m \in L} k_t^{m^{UC}}$ there exist $l: k_t^{l^{CC}} > k_t^{l^{BC}}$ and $m: k_t^{m^{CC}} = \bar{K}_t^m < k_t^{m^{BC}}$. In other words, taking into account an investment potential constraint could affect the result beyond financial deficit.

3.3 Implications for Adoption of New Technologies

One of the key questions motivating our study have been 1) why firms invest in projects with expected negative return limiting their investments in the profitable projects and 2) why firms with similar project choices make different investment decisions. The analysis presented in this sections enables us to revels several rationales for such puzzling behaviour. Firms without financial or investment options constraints are prone to invest:

- into novel projects with $p_t^l < 0$ to enjoy the returns from learning allowing to expanding the production potential, the higher the expected learning return β, the higher the investments;
- in established projects with $p_t^l > 0$ less, the higher the expected learning return;
- Investments in both novel and established technologies are driven by production potential $\bar{K}_t^l$.

Hence, our model suggests that the return on investments consist of the generated profit and learning or production potential expansion. Keeping all the things equal, investments into projects with higher profitability and production potential would be greater. But choosing between the projects with positive and negative return, a firm would prefer the latter one if it has a much greater production potential or if the future ability to exploit the former is limited. Hence, *a-la* R&D projects are developed more intensively, the higher firms ability or expectations regarding internal learning-by-doing captured by β. With improved economics $p_{t+\delta}^l \geq 0$, such projects slow down in development. Thus, financially unconstrained firms could select a portfolio with a large share of commercially unattractive projects and a smaller share of highly profitable projects, balancing the positive financial performance and the expansion of the production potential of the firm.

Our results also highlight the ambiguous role of risk and uncertainty. For instance, the risk of inability to produce fossil fuels in the future would encourage firms to produce more resources today. On the other hand, the uncertainty reduces the role of price expectations and may make the role of production potential more pronounced in the case of the R&D-type projects, intensifying their development.

It is the intertemporal considerations that firms may use to ration its funds, if they are not sufficient to invest into all projects optimally. Firms with financial deficit would

- reduce their investments, relative to the optimal level, more for options with the greater expected return $\hat{p}_{t+1}^l q_t^l$ in the future periods, whereas projects with similar future net price $\hat{p}_{t+1}^l \cong \hat{p}_{t+1}^m$ are rationed based on their productivity;
- allocate a higher deficit share to the similar productivity projects with lower breakeven costs: if $q_t^l = q_t^m$ then $\eta_{t+1}^l > \eta_{t+1}^m$ for $c_t^{l^{be}} < c_t^{m^{be}}$ when risks are the same;
- cut the funding for lower risk $\gamma_t \to 1$ projects more, saving them for the future, keeping all other things equal.

Thus, we establish that though unconstrained case investments are primarily driven by the intertemporal price arbitrage and investment potential, a firm with financial deficit has to consider productivity values and risk explicitly. Comparing the future unit profitability, the firm tries to spare the better projects, which would allow to boost profitability in the future.

It is also important to emphasize the role of technological spill-over effects, which in contrast to the internal learning and technological advances, affect investments into novel as well as established technologies negatively. Though the effect is weaker for innovative firms with high own β.

In sum, the model setup has provided us with enough insights to understand the empirical observations. The conclusions from BC and CC cases are most essential for that. Therefore, in the following analysis of the elasticity for focus on those cases only compensating the disregard of CC case with the discussion on the potential value role.

4. Elasticity of Supply as a Function of Investments

The analysis presented in the previous sections emphasized that the role of the intertemporal net price ratio, along with the changing over time investment potential. With supply dependent on the amount of investment and the allocation of investment across the projects, the elasticity is naturally depends on the investment profile. Using a classical point definition of the elasticity, we write:

$$\epsilon = \frac{\sum_{l\in L} dQ^l}{Q} \cdot \frac{p}{dp} = \frac{p}{dp}\sum_{l\in L} \frac{dQ^l}{Q^l}\frac{Q^l}{Q} = \sum_{l\in L} s^l \left[\frac{p}{dp}\cdot\frac{dQ^l}{Q^l}\right] = \sum_{l\in L} s^l \cdot \epsilon^l \tag{21}$$

$$\epsilon^l = \frac{dQ^l}{dp}\cdot\frac{p}{Q^l} = \frac{p}{Q^l}\cdot q^l \cdot \frac{dk^{l^*}}{\partial p^l} = \frac{p_t}{k^{l^*}}\cdot\frac{dk^{l^*}}{dp} \tag{22}$$

where $s_t^l = \frac{Q_t^l}{Q_t}$ denotes project's share in the total production $Q_t = \sum_l Q_t^l = \sum_l q_t^l k_t^{l^*}(p_t, p_{t+1})$ and ϵ_t^l is the project specific elasticity. Elasticity expressions (21) and (22) though formally correct neglect the fact that supply function depends on the price vector $\vec{p}_t = (p_t, p_{t+1})$, which one can further expand to include more periods. Therefore, the total elasticity of supply shall include a term that would inform of an adjustment in supply related to a change in all the price terms, namely $dp_t = \frac{\partial \vec{p}_t}{\partial p_t}dt + \frac{\partial p}{\partial p_{t+1}}dt$. We redefine the elasticity accordingly:

$$dQ_t = \frac{\partial Q_t}{\partial p_t}dp_t + \frac{\partial Q_t}{\partial p_{t+1}}dp_{t+1} = dQ_t^{near} + dQ_t^{far} \tag{23}$$

$$\epsilon_t = \epsilon_t^{near} + \epsilon_t^{far} \tag{24}$$

Formally speaking (24) does not refer to the short and long-term elasticity, as the same supply function is implied, but merely distinguishes the effects of changes in the current versus future profit extraction possibilities. The time subscript signals about path dependence since investments and supply depend on $\overline{K}_t$. To avoid confusion, we refer to the two elasticity summands as *near* and *far,* respectively.

In the previous section we established that $k_t^{l^*}$ depends on whether the firm is constrained or not. Therefore, we distinguish what affects the elasticity in the case of financially unconstrained and constrained firm. We investigate the elasticity components separately and conclude with the total elasticity discussion.

4.1 The Near-term Price Change

We start with the analysis of the elasticity with respect to p_t reminding that $dp_t = dp_t^l$ but $p_t \neq p_t^l$. Then, referring to optimal investment expression (11) we derive:

$$\epsilon_t^{l\,UC-near} = \frac{p_t}{k_t^{l\,UC}} \cdot \frac{1}{2\beta_t^l \hat{p}_{t+1}^l} = \frac{p_t}{p_t^l + \hat{p}_{t+1}^l(\beta_t^l \bar{K}_t^l - \alpha_t^l)} \tag{25}$$

$$\epsilon_t^{UC-near} = p_t \sum_{l \in L} \frac{s_t^l}{2\beta_t^l k_t^{l\,UC} \hat{p}_{t+1}^l} = p_t \sum_{l \in L} \frac{s_t^l}{p_t^l + \hat{p}_{t+1}^l(\beta_t^l \bar{K}_t^l - \alpha_t^l)} \tag{26}$$

Expressions (25) and (26) include the future expected return, and future price parameter, along with production potential, and technologic parameters. That result explains a wide range of elasticity values and conclusions presented by empirical works when predicting the elasticity. A variety of the future price assumption would translate into a range of $\epsilon_t^{UC-near}$ values, or the firms with different price forecasts would react differently to a price change keeping all other things equal. Similarly, assessments of the production potential would lead to diverse price responses, explaining the sensitivity of producers to the published technical recoverable resource estimates.

Examining the individual project elasticity formula (25) we also notice that the more innovative projects are, i.e. the greater β, the more important the associated production potential is. Projects with higher potential are less reactive to price, driven in their supply by perceived gains in market or production potential. Since projects with smaller production potential are more reactive to price, their .

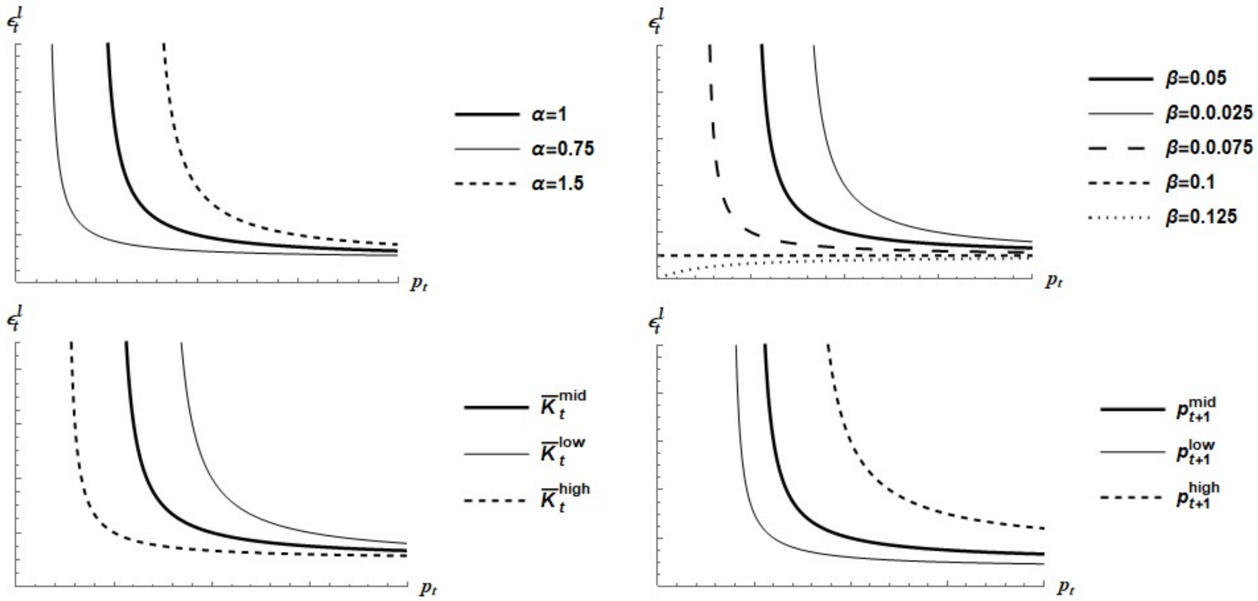


Figure 10. *The effect of technology, project characteristics, and price expectations on the elasticity of investment in a given link (the thick black line represents the same set of parameters across all the plots).*

For illustration purposes, we plot how technology, price expectations, and investment potential affect individual project elasticity (Fig. 10). The graphical illustration suggest several interesting insights. First, one may notice that at higher price levels, the changes in the listed parameters have less effect on the elasticity value, except maybe for the increasing price expectations. Second, we observe that while the effect of technology spill-overs is positive, the impact of learning is non-trivial, as marked in the previous section: high β values lead to a positive link between price and elasticity, whereas low β translates into a negative link. We interpret that finding as follows.

The ability to learn helps to grow investment potential and be less sensitive to price, though fast growth would expand production potential allowing for greater responsiveness. At low β the firm exhausts its potential faster and hence, its ability to react to price shrinks along with its potential. Note, by how much a producing firm would improve technology depends on both the prices and learning capability, determining the optimal investment level. While the result is not new, the technology effect is rarely decomposed into parts dependent on price, learning capability, and investment level, when presented in the elasticity discussion. Our model allows for exploring the channels and respective changes explicitly.

Moving to the limited financing case, we turn to ${k_t^l}^{BC}$ solution given by (20). We derive the investment reaction or elasticity as:

$$\epsilon_t^{l^{BC-near}} = \frac{p_t}{k_t^{l^{BC}}}\left(\frac{1}{2\beta\hat{p}_{t+1}^l} - \frac{\eta_{t+1}^l}{2\beta}\sum_{m\in L}\frac{1}{\hat{p}_{t+1}^m}\right) \tag{27}$$

$$= \frac{p_t}{2\beta k_t^{l^{BC}}}\left(\frac{1-\eta_{t+1}^l}{\hat{p}_{t+1}^l} - \eta_{t+1}^l\sum_{m\in L/l}\frac{1}{\hat{p}_{t+1}^m}\right)$$

Note that at $\eta_{t+1}^l = 0$ investments $k_t^{l^{BC}} = k_t^{l^{UC}}$ and (27) turns into (25). The subtracted term $\eta_{t+1}^l \sum_m \frac{1}{\hat{p}_{t+1}^m}$ explicitly accounts for the impact of the price on the financial deficit and its rationing. Next, to compare the result to the unconstrained case and highlight the role of financial deficit $\delta_t = \sum_{m\in L} k_t^{m^{UC}} - \varepsilon \cdot \Pi_{t-1}$, we rewrite:

$$\epsilon_t^{l^{BC-near}} = \epsilon_t^{l^{UC-near}} \cdot \frac{k_t^{l^{UC}}}{k_t^{l^{BC}}} - \frac{\eta_{t+1}^l}{k_t^{l^{BC}}} \cdot \sum_{m\in L} k_t^{m^{UC}} \epsilon_t^{m^{UC-near}} \tag{28}$$

$$\epsilon_t^{l^{BC-near}} = \epsilon_t^{l^{UC-near}}\left(\frac{k_t^{l^{UC}}(1-\eta_{t+1}^l)}{k_t^{l^{UC}} - \delta_t\eta_{t+1}^l}\right) - \eta_{t+1}^l \cdot \sum_{m\in L/l}\frac{k_t^{m^{UC}}\epsilon_t^{m^{UC-near}}}{k_t^{l^{UC}} - \delta_t\eta_{t+1}^l} \tag{28.1}$$

Owing to non-negativity of investment condition $k_t^{l^{UC}} - \delta_t\eta_{t+1}^l \geq 0$ and $\eta_{t+1}^l \in [0,1]$ under which the hyperbolic deficit function behaviour is such that $\eta_{t+1}^l / k_t^{l^{UC}} - \delta_t\eta_{t+1}^l$ is increasing. Hence, the higher the deficit is, the more it reduces the elasticity. At the same time, the lower the future relative profitability of the project is, the less it is rationed and the closer its elasticity to the unconstrained one.

With project shares $s_t^{l^{BC}} = \frac{Q_t^{l^{BC}}}{Q_t^{BC}} = \frac{q_t^l k_t^{l^{BC}}}{\sum_{m\in L} q_t^m k_t^{m^{BC}}}$ we derive the aggregate production elasticity as:

$$\epsilon_t^{BC-near} = \sum_{l\in L} s_t^l \epsilon_t^{l^{UC}} \cdot \frac{k_t^{l^{UC}}}{k_t^{l^{BC}}} - \sum_{l\in L} s_t^l \frac{\eta_{t+1}^l}{k_t^{l^{BC}}} \cdot \sum_{m\in L} k_t^{m^{UC}} \epsilon_t^{m^{UC}} \tag{29}$$

$$= \sum_{l \in L} \epsilon_t^{l^{UC}} \cdot \frac{q_t^l k_t^{l^{UC}}}{Q_t^{BC}} - \sum_{l \in L} q_t^l \frac{\eta_{t+1}^l}{Q_t^{BC}} \cdot \sum_{m \in L} k_t^{m^{UC}} \epsilon_t^{m^{UC}}$$

We examine how the elasticity in the constrained case differs from the unconstrained again substituting the difference between the investment and production levels, respectively:

$$k_t^{l^{UC}} - k_t^{l^{BC}} = \eta_{t+1}^l \cdot \delta_t, \qquad Q_t^{UC} - Q_t^{BC} = \delta_t \sum_{l \in L} \eta_{t+1}^l q_t^l \tag{30}$$

We substitute (30) in (29) deriving how the elasticity changes due to the deficit and production cut:

$$\epsilon_t^{BC} = \sum_{l \in L} \epsilon_t^{l^{UC}} \cdot \frac{Q_t^{l^{UC}}}{Q_t^{BC}} + \frac{1}{Q_t^{BC}} \sum_{m \in L} k_t^{m^{UC}} \epsilon_t^{m^{UC}} \cdot \frac{Q_t^{UC} - Q_t^{BC}}{\delta_t} \tag{31}$$

$$= \frac{1}{\mathrm{Q}_t^{BC}} \sum_{l \in L} \epsilon_t^{l^{UC}} \left[Q_t^{l^{UC}} + k_t^{l^{UC}} \cdot \frac{Q_t^{UC} - Q_t^{BC}}{\delta_t} \right]$$

$$= \sum_{l \in L} s_t^{l^{UC}} \epsilon_t^{l^{UC}} \left[\frac{Q_t^{UC}}{\mathrm{Q}_t^{BC}} + \frac{Q_t^{UC}(Q_t^{UC} - Q_t^{BC})}{\delta_t \mathrm{Q}_t^{BC} q_t^l} \right]$$

Hence, the elasticity change depends on an individual project rationing cutting its production. To better understand that result, we look at the individual option's weight $\omega_t^l = \frac{Q_t^{UC}}{\mathrm{Q}_t^{BC}} \left[1 + \frac{(Q_t^{UC} - Q_t^{BC})}{\delta_t q_t^l} \right]$. Under $Q_t^{UC} \to Q_t^{BC}$ the multiplier approaches 1 and the difference between two elasticities disappears. Next, we check how close $\frac{(Q_t^{UC} - Q_t^{BC})}{\delta_t q_t^l}$ to 1 or how fast $\eta_{t+1}^m \to 0$ for $l \neq m$ assuming the largest impact of the financing constraint is on l, and other projects are not affected much: $\sum_{m \in L \setminus l} s_t^{m^{UC}} \epsilon_t^{m^{UC}} \frac{Q_t^{UC}}{\mathrm{Q}_t^{BC}}$ $\sim \sum_{m \in L \setminus l} s_t^{m^{UC}} \epsilon_t^{m^{UC}}$.

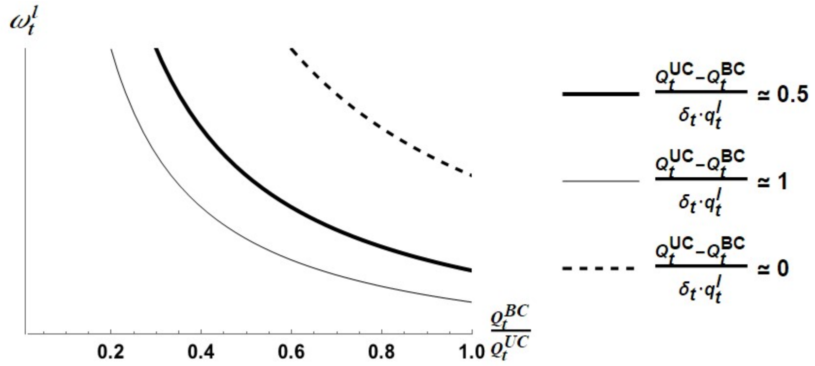


Figure 11.
The adjustment of individual project's contribution to the total elasticity focusing on the relative production loss and effect of financing deficit.

Worth noting that $\frac{(Q_t^{UC} - Q_t^{BC})}{\delta_t q_t^l}$ is determined by the deficit value as well as the project's productivity: the higher the productivity is, the lower the weight value would be (Fig. 11). So the constrained firm is less elastic due to its limited abilities to finance the production response to price. However, the response of less rationed options is closer to the unconstrained elasticity and hence, the firms with lower productivity projects may appear to be less elastic under the same budget deficit. The elasticity of budget constrained *firms* is: a) reduced if the price increases and the firm's deficit increasing, because the firm would like to invest more or b) increased if the price is decreasing and the deficit is decreasing since the firm would prefer to invest less in the unconstrained situation.

We summarize the findings of this subsection in:

Corollary 4 (Near-term Price Elasticity):

The price elasticity of supply is equivalent to the elasticity of firm's investments in individuals projects weighted by their shares in the total portfolio, $\epsilon_t = \sum_{l\in L} s_t^l \cdot \frac{p_t}{k_t^{l*}} \cdot \frac{\partial k_t^{l*}}{\partial p_t^l}$*, and depends on:*

- *the price level: the supply becomes less elastic the price increase;*
- *on financial deficit* δ_t *which affects the elasticity negatively limiting firm's ability to react;*
- *technology externalities* α*, which improves firm's capabilities to react;*
- *internal learning abilities* β *and investment potential* $\overline{K}_t^l$ *negatively, since they make firm less sensitive to price changes letting it rely on its assets;*
- *positively on the future expectations* $\hat{p}_{t+1}^l$*, allowing for future compensation or greater losses.*

4.2 The Effect of Price Expectations

We now proceed with the analysis of supply response to changes in the future ability to generate profit or sell the assets. We start by recalling that the future net price $\hat{p}_{t+1}^l = \gamma(p_{t+1} - c_{t+1}^{l^{be}})$ is a function of risk and expected future breakeven cost, which may change due to the current period investing. In the unconstrained case, the firm would change its investments into each option in according to:

$$\frac{\partial k_t^{l^{UC}}}{\partial p_{t+1}} = -\frac{\gamma^l p_t^l}{2\beta_t^l \hat{p}_{t+1}^{l\,2}} = -\frac{p_t^l}{2\beta_t^l \gamma^l p_{t+1}^{l\,2}} \tag{32}$$

$$\epsilon_t^{l^{UC-fa}} = -\frac{p_{t+1} \cdot p_t^l}{\hat{p}_{t+1}^l \left(p_t^l + p_{t+1}^l\left(\beta_t^l \overline{K}_t^l - \alpha_t^l\right)\right)} \tag{33}$$

From the analysis of investments, we have learned that development of positive return projects would react negatively to a future price increase, a firm would delay investments, whereas investments in R&D type projects with $p_t^l \leq 0$ would increase, as the firm would see the justification of increasing its production potential. Similarly, the relationship $\epsilon_t^{l^{UC-far}} \sim -p_t^l$ suggests the elasticity would be negative for the positive return projects and positive to the negative return ones. We explore the role of the opportunity cost $p_t^l/\hat{p}_{t+1}^l$ using graphical illustration (Fig. 13).

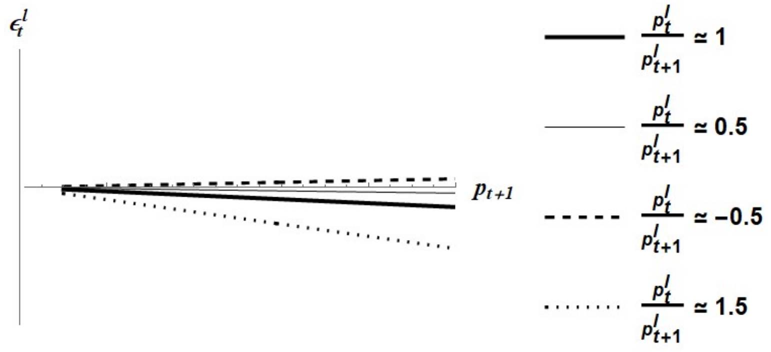


Figure 13.
The effect of the future price expectations change on the unconstrained firm's elasticity.

The plot of the elasticity reveals that the higher opportunity cost are, the higher the absolute value of the elasticity and the more reactive it is to the future price level. The production potential and technology parameters enter ${\epsilon_t^l}^{UC-f}$ in a similar way as ${\epsilon_t^l}^{UC-near}$ and so the discussion and conclusions from the previous subsection apply.

Weighting the project elasticities by their production shares, we derive the aggregate elasticity as:

$$\epsilon_t^{UC-far} = \frac{p_{t+1}}{2}\sum_{l\in L}\frac{s_t^l}{\gamma^l\beta_t^l {k_t^l}^{UC}\left(p_{t+1}-c_{t+1}^{lbe}\right)^2} = \frac{p_{t+1}}{2Q_t}\sum_{l\in L}\frac{q_t^l}{\gamma^l\beta_t^l\left(p_{t+1}-c_{t+1}^{lbe}\right)^2} \tag{34}$$

The key insight that we derive from (34) is about uncertainty. Converging to the other models on investments and supply dynamics, we find that the higher the uncertainty is, the less sensitive the firm to the changes in the price expectations. Moreover, the elasticity is influenced more by the projects with lower uncertainty and lower breakeven cost or higher productivity. Besides, projects with a higher learning return on investment are again are less sensitive to price expectations, whereas the projects with higher current productivity are more responsive.

Analysing BC case, we recall that price expectations affect not only ${k_t^l}^{UC}$ but also the budget rationing: the projects with higher future profitability are rationed more. We derive:

$$\frac{\partial {k_t^l}^{BC}}{\partial p_{t+1}} = \frac{\partial {k_t^l}^{UC}}{\partial p_{t+1}} - \eta_{t+1}^l\frac{\partial \delta_t}{\partial p_{t+1}} - \frac{\partial \eta_{t+1}^l}{\partial p_{t+1}}\delta_t \tag{35}$$

$${\epsilon_t^l}^{BC-far} = {\epsilon_t^l}^{UC}\left(\frac{{k_t^l}^{UC}}{{k_t^l}^{BC}} - \eta_{t+1}^l\sum_{m\in L}\frac{{k_t^m}^{UC}}{{k_t^l}^{BC}}\right) - \frac{p_{t+1}}{{k_t^l}^{BC}}\cdot\eta_{t+1}^l\delta_t\left(\frac{1}{\hat{p}_{t+1}^l} - \frac{\sum_{m\in L} q_t^m}{\sum_{m\in L}\hat{p}_{t+1}^m q_t^m}\right) \tag{36}$$

Looking at (35), we shall note that $\frac{\partial \eta_{t+1}^{l}}{\partial p_{t+1}} = const$ if the future net price for all the projects is similar. Then, the financial deficit reduces $\epsilon_t^{l^{BC-}}$ negatively. Second, we must recognize that a change in p_{t+1} may affect the project space, since we consider only projects with the positive future value, though the current value can be negative. In addition, the sign of the derivative would depend on how the given project breakeven cost value relative to the others. We show how the sign of the derivative and therewith the effect of the deficit may change in Figure 14.

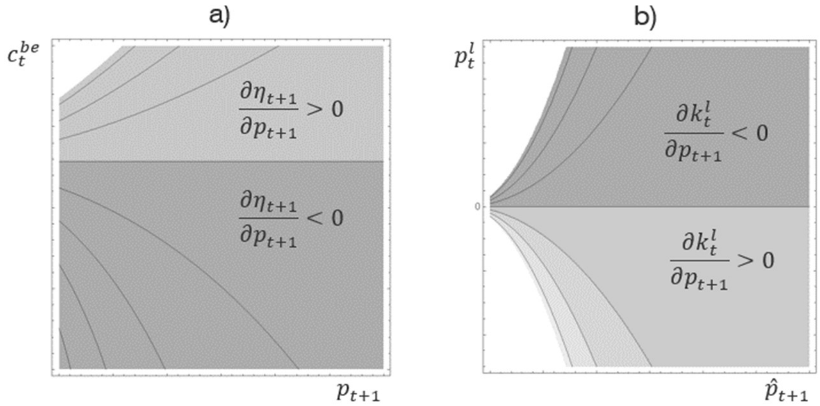


Figure 14.
The effect of change in price expectations on the financial deficit rationing and the deficit value.

The multiplier in front of the deficit may be positive as well as negative and so does $\frac{\partial \delta_t}{\partial p_{t+1}} = \frac{\partial \sum_{m \in L} k_t^{m^{UC}}}{\partial p_{t+1}}$. Thus, elasticity of projects with low breakeven cost or a higher future unit profitability, that have been rationed more, depends negatively on the deficit, in contrast to the projects with lower future value, which become more sensitive to changes in the expectations (Fig. 14a).

The effect of a price change on the deficit is also non-trivial and depends on the changes in the optimal unconstrained investments, in which the role of the future price dependent on the sign of the current net price. Hence, we find that the sign and the value of the second summand in (35) may vary (Fig. 14b). For the more novel projects with $p_t^l < 0$ are in the firm's portfolio, the greater the value of $\frac{\partial \delta_t}{\partial p_{t+1}}$. Yet, the high share of established projects with $p_t^l > 0$ would lead to $\frac{\partial \delta_t}{\partial p_{t+1}} < 0$ or $-\frac{p_{t+1}}{k_t^{l^{BC}}} \eta_{t+1}^{l} \frac{\partial \delta_t}{\partial p_{t+1}} > 0$. And so, the more innovative the firm, the more negative or low return projects it has, the more sensitive it is to the future price. A firm with certain and established projects is less sensitive to the future price changes.

Since the individual project elasticities may take different signs and vary depending on the project characteristics, especially relative breakeven cost and the current net price, the aggregate $\epsilon_t^{BC^{far}}$ elasticity is parameter-dependent. We conclude with a counterintuitive result that the elasticity of a financially constrained firm may exceed that one without any constraints. Furthermore, the sign of the unconstrained elasticity is ambiguous, the deficit could decrease or increase elasticity, and hence, the increase in price expectations could make the firm less willing to invest relaxing the budget constraint and increasing the elasticity. On the other hand, if the change in expectations makes the firm eager to invest more, the budget deficit increases and supply becomes less elastic. Financial scarcity would prevent the firm from changing its investment and therewith, production levels. If the firm is able to react, it can invest to become less- or unconstrained. In the latter case, the conclusions provided earlier would be applicable. We skip the cumbersome expressions for the aggregate ϵ_t^{BC-} and conclude with:

Corollary 5 (Future Price Elasticity):

The future price elasticity of supply turn negative as the firms face a change in intertemporal preferences or stay positive, if the firm remains profitability driven, so the supply is

- *less elastic if a price expectation change encourages to invest more today making the budget deficit more pronounced, or*
- *more elastic if the price change discourages investments relaxing the budget constraint allowing to the shift investments into the future.*

4.3 The Total Price Elasticity of Supply

We now proceed with the analysis of supply response to changes in the future price expectations. We start by recalling that firm's investments $k_t^{l^*} \sim f\left(\frac{1}{\hat{p}_{t+1}^l}\right)$ as a function of expectations. In the unconstrained case, the firm would change its investments into each option in according

$$\epsilon_t^{l^{UC-near}} + \epsilon_t^{l^{UC-far}} = \frac{p_t}{p_t^l + \hat{p}_{t+1}^l(\beta_t^l \bar{K}_t^l - \alpha_t^l)} - \frac{\gamma \cdot p_{t+1} \cdot p_t^l}{\hat{p}_{t+1}^l\left(p_t^l + \hat{p}_{t+1}^l(\beta_t^l \bar{K}_t^l - \alpha_t^l)\right)} \tag{37}$$

$$= \frac{1}{p_t^l + \hat{p}_{t+1}^l(\beta_t^l \bar{K}_t^l - \alpha_t^l)}(p_t - p_{t+1} \cdot \frac{p_t^l}{p_{t+1}^l}) \tag{38}$$

We see how the near elasticity can be reduced by our considerations of the future price changes and may even outweigh leading to the total elasticity being negative. The second factor in (x) shows helps understand why many industries and firms report close to zero elasticity of supply values due to $\frac{p_t}{p_{t+1}} \to \frac{p_t^l}{p_{t+1}^l}$. We also find that since $\frac{p_t}{p_{t+1}} < \frac{p_t^l}{p_{t+1}^l}$ is equivalent to $\frac{c_t^{l^{be}}}{c_{t+1}^{l^{be}}} < \frac{p_t}{p_{t+1}}$, the supply elasticity for a given project is negative as long as the intertemporal price change is greater than the intertemporal breakeven cost change. In other words, the negative elasticity result results from intensified investments in R&D-type projects driven by changes in the future ability to extract profit or growth in the value of the production potential. Investing more in low or negative return projects with lower productivity, the firm decreases its supply while the current price change may be positive. Thus, an increase in p_{t+1} would increase investments in $p_t^l \leq 0$ projects, and if the share of such projects prevails in the firm's portfolio, due to the investment potential or low technological gains for higher productivity projects, the total firm supply elasticity is negative. If the share of production from such projects is greater than the share of positive return projects, than the total elasticity is negative.

Combining the expressions for the financially constrained cases, we highlight the effect of the current and future prices on the deficit and rationing. Deficit depends positively on current prices but negatively on the future price, and hence, the weighted sum $p_t \frac{\partial \delta_t}{\partial p_t} + p_{t+1} \frac{\partial \delta_t}{\partial p_{t+1}}$ may turn to be positive as well as negative. In the previous subsection we have also revealed that $\frac{\partial \eta_{t+1}^l}{\partial p_{t+1}} \gtrless 0$.

The summary expression for the elasticity:

$$\epsilon_t^{l\,BC-near} + \epsilon_t^{l\,BC-far} = \frac{p_t}{k_t^{l\,BC}}\left(\frac{\partial k_t^{l\,UC}}{\partial p_t} - \eta_{t+1}^l \frac{\partial \delta_t}{\partial p_t}\right) + \frac{p_{t+1}}{k_t^{l\,BC}}\left(\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} - \eta_{t+1}^l \frac{\partial \delta_t}{\partial p_{t+1}} - \frac{\partial \eta_{t+1}^l}{\partial p_{t+1}}\delta_t\right) \tag{39}$$

$$\sim p_t\left(\frac{\partial k_t^{l\,UC}}{\partial p_t} - \eta_{t+1}^l \sum_l \frac{\partial k_t^{l\,UC}}{\partial p_t}\right) + p_{t+1}\left(\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} - \eta_{t+1}^l \sum_l \frac{\partial k_t^{l\,UC}}{\partial p_{t+1}}\right) - p_{t+1}\delta_t \frac{\partial \eta_{t+1}^l}{\partial p_{t+1}}$$

suggests that for some projects, the negative elasticity phenomenon may stem from the large deficit and future price values in combination with $\frac{\partial \eta_{t+1}^l}{\partial p_{t+1}} > 0$. Note that we have shown that is likely to occur for the projects with the relatively high breakeven cost values, like the novel technologies.

The rationing term also plays an important role in determining the sign of the total elasticity and the interdependency of the projects' reactions. Especially, higher the deficit value and the greater the rationing turn for the project, e.g. due to the high productivity, the greater the possibility for the project to exhibit negative elasticity. As the rationing term increases the elasticity is determined by the effect of price on the rival projects:

$$\epsilon_t^{l\,BC-near} + \epsilon_t^{l\,BC-far} \xrightarrow{\eta_{t+1}^l \to 1} -\eta_{t+1}^l \left(p_t \sum_{L/l} \frac{\partial k_t^{l\,UC}}{\partial p_t} + p_{t+1} \sum_{L/l} \frac{\partial k_t^{l\,UC}}{\partial p_{t+1}}\right) \tag{40}$$

And since both summands in the brackets are positive in the case of novel projects, we confirm that individual projects may have negative elasticity due to the intertemporal price change effect and cross-project deficit distribution effect. With $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} < 0$ for mature projects, we also suggest that it is innovative firm, with a greater share of novel projects that are likely to have negative elasticity of supply.

To disentangle the complexity of the total elasticity behaviour further, we use simulations and graphical illustrations. Figure 15 contains four rows of plots showing the percentage change in an individual project supply under different breakeven cost assumptions. Since $\hat{p}_{t+1}^l$ stays in the denominator of the optimal investment formula, the third column of plots reveals the discontinuity at $p_{t+1} = c_{be}^l$. With the near and far elasticities in mind, in the first two rows of Figure 15 we exhibit separately changes in the supply to a unit change in the current (first row) versus future (second row) price. The third row reveals a combined effect, namely a change in supply corresponding to a unit change in both price values. Finally, the last row presents plot illustrating the effect of a non-zero financial deficit. We perform all the calculations assuming that investment potential and technological expectations are the same across all the projects and setting the uncertainty parameter equal to 1.

In case of a zero financial deficit, the contour plots in the third row show how $\frac{p_t}{p_{t+1}} = 1$ line divides the plot into areas with positive and negative supply change associated with a unit price increase. In other words, one can see how the total elasticity takes negative values at $p_t > p_{t+1}$, as incentives to spare the project to extract its value in the future outweigh the immediately expected profit. Interesting that the line determining the elasticity sign switch remains the same, but the shape of contours changes with the project profitability as demonstrated by the shading patters. Looking at the first and second row plots, one can notice that the evolution of contours is determined by the breakeven cost value and symmetry lines $p_t = c_{be}^l$ and $p_{t+1} = c_{be}^l$.

The non-trivial nature of the supply response captured by (39) is also reflected in the plot of the fourth row. Worth noticing that the first two columns of plots have price axis cross at values above the breakeven cost avoid discontinuity, which present only on the last column of plots. As a result, it is only on the bottom right plot that one can see that the breakeven cost value set a type of a gravity centre for the contours propagation. Under financial deficit the properties of the sign-changing line are inherited by the non-linear contour and the response can take positive and negative values both above and below $p_t = p_{t+1}$ line.

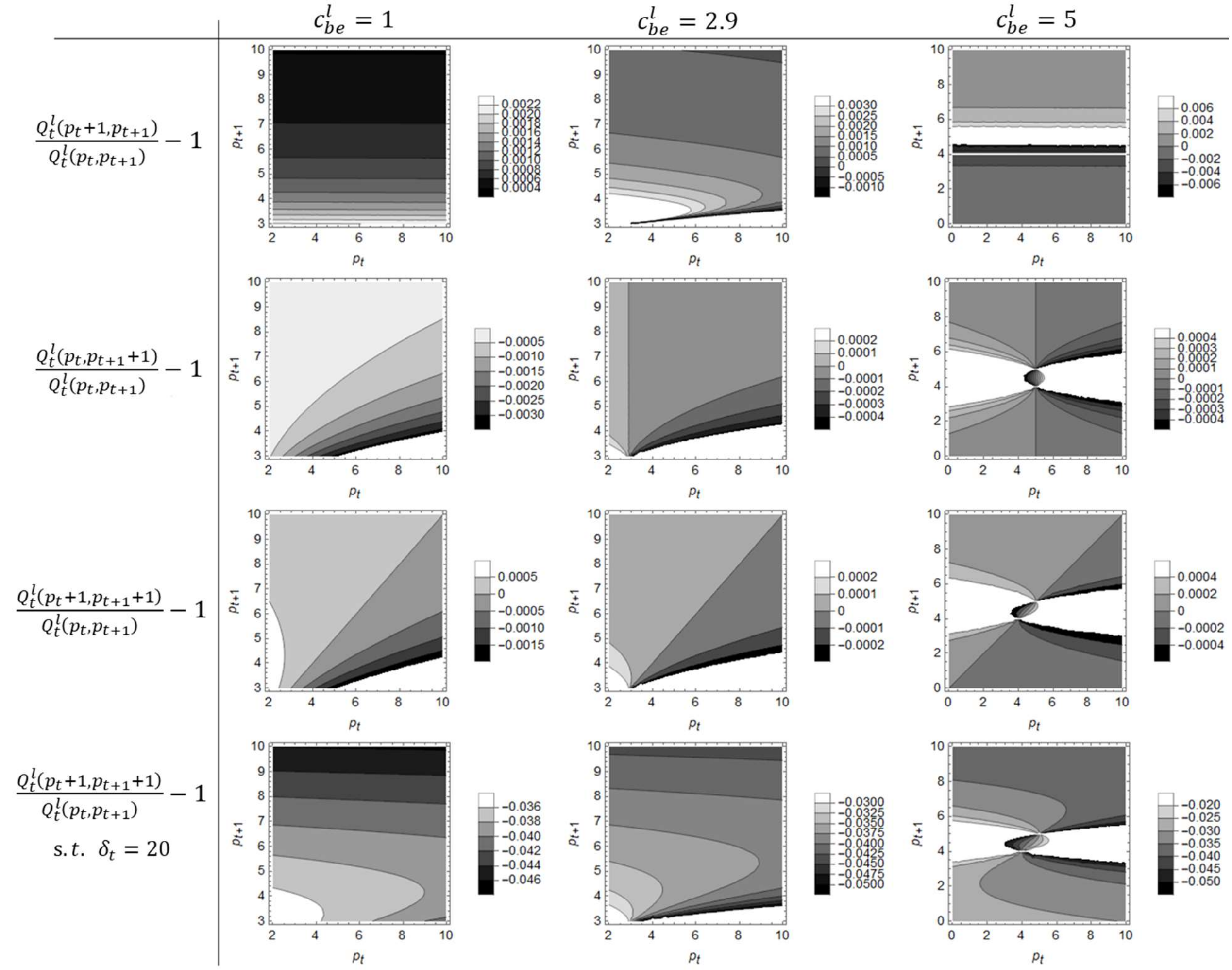


Figure 15.
The effect price levels, breakeven costs, and financial deficit on the supply response to unit price change.

We picked the breakeven cost and other values, including price levels, to reflect the situation around the Marcellus play to be able verify our theoretical findings. We leave a thorough empirical investigation for future work and rely on the facts and analysis presented by Ikonnikova et al (2018). We turn to the Marcellus well statistics with wells grouped based on their profitability index. Following the discussion in the original report, we remove ~10% of wells with profitability index <0.5 to avoid errors associated with wrong reporting and missing data and account only for well which allow for the positive profit and/or asset value. The remaining wells are split into tiers. Wells with profitability index 0.5 to 0.85 are considered to be negative return projects with $p_t^l < 0$, whereas wells index values of 0.85 to 1 could be breakeven allowing for some error in cost calculations, royalty contracts, or differences in companies' accounting practices. The plot of investment dynamics across different groups shows close correlation to the natural gas price for all except for the negative return, or a-la R&D projects (Figure 16).

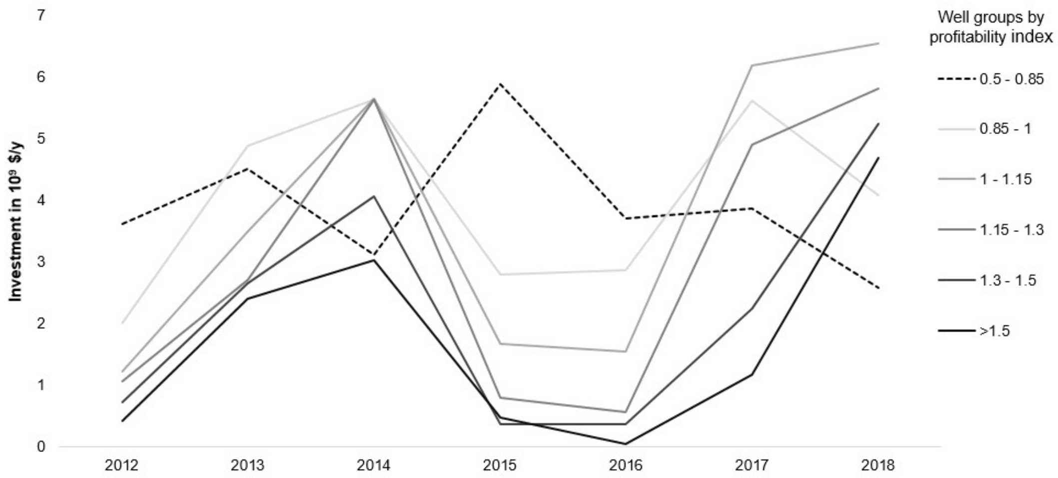


Figure 16.
Differences in investment dynamics across different profitability projects in the Marcellus play.

To confirm the insights from our model, we turn to Fig. 15 and use some information on improvements in production efficiency and future price forecasts. Using the base-case price projections delivered every year by the U.S. Energy Information Administration, we estimate the near-term and future prices and difference in relative change over time. If we ignore the change in breakeven costs and apply the unconstrained solution (11) we can estimate:

$$k_{2013}^{0.5-085\,UC}|_{p_t=3.63} = \frac{p_t^l}{2\beta\hat{p}_{t+1}^l} - \frac{\alpha}{2\beta} + \frac{\overline{K}_t^l}{2} \approx -\frac{0.37}{2\cdot 0.15\cdot 0.5} - \frac{1.05}{2\cdot 0.15} + \frac{\overline{K}_{2013}^l}{2} = -6.3 + \frac{\overline{K}_{2013}^l}{2}$$

$$k_{2014}^{0.5-085\,UC}|_{p_t=3.78} \approx -\frac{0.22}{2\cdot 0.10\cdot 0.25} - \frac{1.05}{2\cdot 0.10} + \frac{\overline{K}_{2014}^l}{2} = -8.9 + \frac{\overline{K}_{2014}^l}{2}$$

$$k_{2015}^{0.5-08\;\,UC}|_{p_t=1.71} \approx -\frac{1.3}{2\cdot 0.10\cdot 1.2} - \frac{1.0}{2\cdot 0.10} + \frac{\overline{K}_t^l}{2} = -5.5 + \frac{\overline{K}_{2015}^l}{2}$$

Hence, even assuming the change in the production potential is small, find that despite increasing p_t the remaining fairly constant p_{t+1} results in the decreasing first summand, so the investments would increase and the elasticity would be negative. The inclusion of the deficit term with the rationing multiplier might explain the value of the increase in 2015 investments but detailed empirical analysis is beyond the scope of this paper and we leave such investigation for future research satisfied with the fact that the solution of our model enables us to explain the differences in elasticity signs of supply from various projects.

5. Implications and Venues for Future Research

We initiated the modelling exercise presented in this paper, puzzled by the repeatedly reported negative elasticity of supply phenomenon, which the majority of previous studies, including Gomes (2011) attributed to estimation error or neglected as a short-term event. With insights from the U.S. unconventional oil and gas supply, we developed a model that considers the necessity to invest in both value extraction and value expansion. Our model aims to represent producers who may run out of investment options unless they invest in new technologies or projects expanding future production capabilities. Examining incentives for supply, we build a bridge between exhaustible resource literature and R&D models. Both strands of literature traditionally neglect the effect of financial deficit, which forces producers to account for intertemporal and across projects opportunity costs to ration funds. The solution presented in the paper captures the interplay between intertemporal and cross-project valuations. We believe that the derived understanding is particularly useful in envisioning how the energy transition may unfold, predicting how producers would transform their portfolios.

The energy industry has been reporting decreasing the average return on investments, with the major energy company Exxon being out of the top 10 of the S&P 500. Despite the continuous growth in fossil energy consumption, the energy prices experienced extreme volatility, with unforeseen fluctuations as well as expected adjustments. In this context, the major industry players, like BP, Equinor (former Statoil), Shell, have been adjusting their investment strategies and asset portfolios. Introducing novel high-cost projects such as hydrogen technologies and divesting from proven profitable technologies assets, the companies have often been criticized for taking a high risk. Our model allows seeing what may justify such decisions even under high uncertainty.

The derived elasticity suggests that the transformation, triggered by changes in price expectations, future regulatory uncertainty, and expectations regarding the growth in the production potential of new technologies, would have a non-intuitive effect on the total (e.g. energy) supply. Therefore, however complex, the presented model may become a useful tool for policy and regulatory analysis helping estimate, among others, the effect of changes in future price or cost regulations and financial support.

Affecting the views on production or investment potential regulators or public can incentivize firms and the entire industry to invest more into innovative low-carbon projects. The latter could make firms less sensitive to price and thus, improve consumer benefits, confirming that innovative firms and industries are better for the economy. The results of our study provide useful insights about strategies optimal for firms in the energy and other industries in the context of low-carbon transition.

The developed framework, however, could be further expanded to differentiate the channels for an increase in production potential, i.e. productivity versus investment potential boost. The differentiation would help to target investment stimulus. In this context, one may also investigate the effect of capital cost and external versus internal financing and focus on the determinants of the uncertainty and the value of the discounting factor, which may vary across the projects. Our model allows for new discoveries and divestments, but we have not studied the role of those explicitly, also leaving room for research questions related to stranded resources.

A different line of research that may continue our analysis relates to the industry dynamics. Financial economics literature often discusses the differences in large and small firm motivation, i.e. total value vs. profit maximization, respectively. In the context of our model, one may analyze how and why large firms appear more innovative when compared to small counterparts. On the other hand, start-ups focused on the investment and production potential, or value of the growth assets, are hyper-innovative compare to the large firms, which have to generate profit and follow a stricter financial discipline.

To sum up, we see a variety of applications, extensions, and enhancements for the presented model both theoretical, applied, and empirical. Those stemming from the energy industry observations, the model shall be equally usable in other industries with the correct specification and parameter assessments. This study shall be of interest of industrial and financial economists but provides food for thought for policymakers and regulators as it helps explain and accommodate the diversity of previous insights regarding investments and supply.

References

Abel, A., Dixit, A., Eberly, J., Pindyck, R., 1996, Options, the Value of Capital, and Investment, the Quartely Journal of Economics

Archer, N. P., & Ghasemzadeh, F. (1999). An integrated framework for project portfolio selection. International Journal of Project Management, 17(4), 207–2016.

Armstrong, M., & Huck, S. (2010). Behavioral economics as applied to firms: A primer.

Arora, V., 2014, Estimates of the Price Elasticities of Natural Gas Supply and Demand in the United States, MPRA Paper No. 54232, https://mpra.ub.uni-muenchen.de/54232/MPRA Paper No. 54232

Baddeley, M. C., (2012), Investment Theory and Analysis, Palgrave Macmillan, New York.

Benaija, K., Kjiri, L. (2014). Project portfolio selection: Multi-criteria analysis and interactions between projects. International Journal of Computer Science Issues, 11 (6) 134-143

Benes, J., Chauvet, M., Kamenik, O., Kumhof, M., Laxton, D., Mursula, S., & Selody, J., 2015, The future of oil: Geology versus technology. International Journal of Forecasting, 31(1), 207–221. https://doi.org/10.1016/j.ijforecast.2014.03.012

Beviá, C., Corchon, L., & Yasuda, Y. (2015). Oligopolistic Equilibrium and Financial Constraints. The American Economic Review, 79(1), 14-31.

Beviá, C., Corchón, L. C., & Yasuda, Y. (2020). Oligopolistic equilibrium and financial constraints. RAND Journal of Economics, 51(1), 279-300.

Bolton, P.,Wang, N., and J. Yang. 2014. Investment under uncertainty and the value of real and financial flexibility. Working Paper, Columbia University

Brockway, P. E., Owen, A., Brand-Correa, L. I., & Hardt, L., 2019, Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nature Energy, 4(7), 612–621. https://doi.org/10.1038/s41560-019-0425-z

Browning, J., Tinker, S. W., Ikonnikova, S., Gülen, G., Potter, E., Fu, Q., ... & Medlock, K. (2013). Barnett study determines full-field reserves, production forecast. Oil and Gas Journal, 111(9), 88-95.

Caballero, Ricardo J & Pindyck, Robert S, 1996. "Uncertainty, Investment, and Industry Evolution," International Economic Review, Department of Economics, University of Pennsylvania and Osaka University Institute of Social and Economic Research Association, vol. 37(3), pages 641-662, August

Campiglio, E., Kemp-Benedict, E., Godlin, A., Matikainen, S., 2017, Tightening Links Between Financial Systems and the Low-Carbon Transition, in book: Economic Policies since the Global Financial Crisis, edt. by Malcolm Sawyer, Philip Arestis

Campiglio, E., von Jagow, A., 2019, Climate Risks in Financial Assets, Council on Economic Policies, Discussion Paper 2019/2

Chapman, A., Itaoka, K., Farabi-Asl, H., Fujii, Y., & Nakahara, M., 2020, Societal penetration of hydrogen into the future energy system: Impacts of policy, technology and carbon targets. International Journal of Hydrogen Energy. doi:10.1016/j.ijhydene.2019.12.112

Covert, T., Greenstone, M., & Knittel, C. R., 2016, Will We Ever Stop Using Fossil Fuels? Journal of Economic Perspectives, 30(1), 117–138. https://doi.org/10.1257/jep.30.1.117

Carol Dahl, Thomas E Duggan, 1996, U.S. energy product supply elasticities: A survey and application to the U.S. oil market, Resource and Energy Economics, Vol. 18 (3), 243-263, https://doi.org/10.1016/S0928-7655(96)00009-7

CDP, 2019, Major Risk or Rosy Opportunity: Are companies ready for climate change? 2019 Climate Change Report.

Chakravorty, Ujjayant, Bertrand Magne, and Michel Moreaux. 2006. "A Hotelling Model with a Ceiling on the Stock of Pollution." Journal of Economic Dynamics and Control, 30(12): 2875–2904

Chakravorty, U., Moreaux, M., & Tidball, M. (2008). Ordering the Extraction of Polluting Nonrenewable Resources. American Economic Review, 98(3), 1128–1144. doi:10.1257/aer.98.3.1128

Cooper, R. G., & Edgett, S. J. (2001). Portfolio management for new products: picking the winners. Product Development Institute, Ancaster, Ontario, Canada.

David J. Denis, Valeriy Sibilkov, 2010, Financial Constraints, Investment, and the Value of Cash Holdings, Review of Financial Studies 23(1):247-269, DOI: 10.1093/rfs/hhp031

DeCanio, S. J., & Watkins, W. E.,1998, Investment in Energy Efficiency: Do the Characteristics of Firms Matter? Review of Economics and Statistics, 80(1), 95–107. https://doi.org/10.1162/00346539855736

David J. Denis and Valeriy Sibilkov, 2010, Financial Constraints, Investment, and the Value of Cash Holdings, The Review of Financial Studies, Vol. 23, No. 1 (Jan., 2010), pp. 247-269

Deign, L., 2019, The Reality Behind Green Hydrogen's Soaring Hype: Renewably produced hydrogen has great potential and some powerful allies. But it's not a decarbonization panacea, Wood Mackenzie Power & Renewables (formerly GTM Research), Nov 18, 2019.

Dixit, A. & Pindyck, R., 1994, Investment under uncertainty. Princeton, N.J: Princeton University Press

EIA, 2014, Some Appalachian natural gas spot prices are well below the Henry Hub national benchmark, Report by Energy Information Administration, October 15, 2014

EIA, 2016, Trends in U.S. Oil and Natural Gas Upstream Costs, Report by Energy Information Administration, March 2016

EIA, 2017, Natural gas pipeline projects lead to smaller price discounts in Appalachian region, Report by Energy Information Administration

Equinor, 2019, Energy Perspectives 2019: Long-term macro and market outlook

Fisher, W. L., Angino, E. E., Claypool, G. B., Henshaw, P. C., Knapp, R. M., Leighton, M.W., Nur, A. M., Thomasson, M. R., and Vail, P. R., 1988, Scientific drilling and hydrocarbon resources: National Academy Press, National Academy of Sciences, Washington, D.C.

Fuss, C., & Vermeulen, P. (2008). Firms' investment decisions in response to demand and price uncertainty. Applied Economics, 40(18), 2337–2351. doi:10.1080/00036840600959909

Gaudet, Gérard, Michel Moreaux, and Stephen W. Salant. 2001. "Intertemporal Depletion of Resource Sites by Spatially Distributed Users." American Economic Review, 91(4): 1149–59

Giaccotto, C., Santerre, R. E., & Vernon, J. A. (2005). Drug prices and research and development investment behavior in the pharmaceutical industry. The Journal of Law and Economics, 48(1), 195-214.

Gian Luca Clementi and Hugo A. Hopenhayn, 2006, A Theory of Financing Constraints and Firm Dynamics, The Quarterly Journal of Economics, Vol. 121, No. 1 (Feb., 2006), pp. 229-265. https://doi.org/10.2139/ssrn.314274

Gnann, T., Stephens, T. S., Lin, Z., Plötz, P., Liu, C., & Brokate, J. (2018). What drives the market for plug-in electric vehicles? - A review of international PEV market diffusion models. Renewable and Sustainable Energy Reviews, 93, 158–164. doi:10.1016/j.rser.2018.03.055

Gomes, J. F. (2001). Financing investment. American Economic Review, 91(5), 1263-1285.

Grim, D. M., & Berkowitz, D. B. (2020). ESG, SRI, and impact investing: A primer for decision-making. The Journal of Impact and ESG Investing, 1(1), 47-65.

GSIA, 2018, The Global Sustainable Investment Review 2018, Trend Report 2018, Global Sustainable Investment Alliance

Gülen, G., Ikonnikova, S., Browning, J., Tinker, S.W. 2015. Haynesville shale production outlook. SPE Economics & Management, Vol. 7(4).

Gulen, G., Ikonnikova, S., Browning, J., and Tinker, S. 2014. Fayetteville shale production outlook. SPE Economics & Management, Vol. 7(2).

Halcoussis, D., & Lowenberg, A. D.,2019, The effects of the fossil fuel divestment campaign on stock returns. The North American Journal of Economics and Finance, 47, 669–674. https://doi.org/10.1016/j.najef.2018.07.009

Hausman, Catherine and Ryan Kellogg (2015). "Welfare and Distributional Implications of Shale Gas," Brookings Papers on Economic Activity, Spring..

Hellweg, S., Hofstetter, T. B., & Hungerbuhler, K. (2003). Discounting and the environment should current impacts be weighted differently than impacts harming future generations?. The International Journal of Life Cycle Assessment, 8(1), 8.

Hosseini, S. H., Shakouri, H., Kazemi, A., Zareayan, R., & Mousavian, M. (2019). A system dynamics investigation of project portfolio management evolution in the energy sector. Kybernetes.

Hotelling, Harold. 1931. “The Economics of Exhaustible Resources.” Journal of Political Economy, 39(2): 137–75

Hunt, R., Killen, C. P., & Morcos, M. S. (2008). Modelling resource allocation of R&D project portfolios using a multi-criteria decision-making methodology. International Journal of Quality & Reliability Management.

IEA, 2020, World Energy Investment 2020, IEA, Paris https://www.iea.org/reports/world-energy-investment-2020

IEA, 2019a, The Oil and Gas Industry in Energy Transitions: Insights from IEA analysis, International Energy Agency

IEA, 2019b, World Energy Outlook 2019, IEA, Paris, www.iea.org/weo2019

IHS, 2019, Oil and Gas Company Climate Indicators Highlight Consensus on Risks, Divergence in Response, Climate and Carbon Insight, IHS Markit

Ikonnikova, S., Smye, K., Browning, J., Dommisse, R., Gülen, G., Hamlin, S., Tinker, S. W., Male, F., McDaid, G., Vankov, E., 2018, Report on Update and Enhancement of Shale Gas Outlooks, DOE Technical Report, http://doi.org/10.2172/1479289

Ikonnikova, S., Male, F., Reedy, R., 2017. Projecting Water Footprint under Different Price Scenarios: Case study of the Eagle Ford Shale, Environmental Science and Technology, Vol. 51 (24).

Ikonnikova, S., Gülen, G., Browning, J. 2016. Impacts of Price Differentials, Taxation, and Costs on Shale Gas Drilling: A Marcellus Case Study, SPE/IAEE Hydrocarbon Economics and Evaluation, SPE-179985.

Ikonnikova, S. and Gülen, G. 2015. Impact of low prices on shale gas production strategies. Energy Journal, Vol. 36.

Ilyina, A., & Samaniego, R. (2012). Structural change and financing constraints. Journal of Monetary Economics, 59(2), 166-179.

IRENA, 2012, Renewable Energy Technologies: Cost Analysis Series, Wind Power, Vol. 1, Issue 5/5, June 2012

Jin, M., Zhao, S., & Kumbhakar, S. C. (2019). Financial constraints and firm productivity: Evidence from Chinese manufacturing. European Journal of Operational Research, 275(3), 1139-1156.

Kang, W., Lee, K., & Ratti, R. A. (2014). Economic policy uncertainty and firm-level investment. Journal of Macroeconomics, 39, 42–53. doi:10.1016/j.jmacro.2013.10.006

Kellogg, R., 2011, Learning by Drilling: Interfirm Learning and Relationship Persistence in the Texas Oilpatch. The Quarterly Journal of Economics, 126(4), 1961–2004. https://doi.org/10.1093/qje/qjr039

Levine, O., & Warusawitharana, M. (2019). Finance and productivity growth: Firm-level evidence. Journal of Monetary Economics.

Mason, C. F., Muehlenbachs, L. A., & Olmstead, S. M., 2015, The Economics of Shale Gas Development. Annual Review of Resource Economics, 7(1), 269–289. https://doi.org/10.1146/annurev-resource-100814-125023

Mason, C. F, Roberts, G., 2018, Price Elasticity of Supply and Productivity: An Analysis of Natural Gas Wells in Wyoming, Energy Journal 39 (S1):79–101. doi:10.5547/01956574.39.SI1.cmas.

MacKay, P. (2003). Real Flexibility and Financial Structure: An Empirical Analysis. The Review of Financial Studies, 16(4), 1131-1165. Retrieved January 6, 2021, from http://www.jstor.org/stable/1262739

Male, F., Marder, M. P., Browning, J., Ikonnikova, S., & Patzek, T. (2016, May). Marcellus wells' ultimate production accurately predicted from initial production. In SPE Low Perm Symposium. Society of Petroleum Engineers.

McKinsey, 2019, Global Energy Perspective 2019: Reference Case, Energy Insights, Jan 2019

Miao, J., 2005, Optimal Capital Structure and Industry Dynamics. The Journal of Finance, 60(6), 2621–2659. https://doi.org/10.1111/j.1540-6261.2005.00812.x

Mizik, N., & Jacobson, R. (2003). Trading off between value creation and value appropriation: The financial implications of shifts in strategic emphasis. Journal of marketing, 67(1), 63-76.

Morcos, M. (2008). Modelling resource allocation of R&D project portfolios using a multi-criteria decision-making methodology. International Journal of Quality & Reliability Management, 25, 72-86.

Newell, Richard G., Brian C. Prest, and Ashley Vissing (2016). "Trophy Hunting vs. Manufacturing Energy: The Price Responsiveness of Shale Gas," NBER Working Paper 22532, August, National Bureau of Economic Research.

Nicholas, J., Ledwith, A., & Perks, H. (2011). New product development best practice in SME and large organisations: theory vs practice. European Journal of Innovation Management.

Pammolli, F., Magazzini, L. & Riccaboni, M. The productivity crisis in pharmaceutical R&D. Nat Rev Drug Discov 10, 428–438 (2011). https://doi.org/10.1038/nrd3405

Patzek, T. W., Male, F., & Marder, M., 2013, From the Cover: Cozzarelli Prize Winner: Gas production in the Barnett Shale obeys a simple scaling theory. Proceedings of the National Academy of Sciences, 110(49), 19731–19736. https://doi.org/10.1073/pnas.1313380110

Pindyck, R., 1991, Irreversibility, Uncertainty, and Investment. Journal of Economic Literature 29, no. 3, 1110–1148

Ponce, M., & Neumann A., 2014, Elasticities of Supply for the US Natural Gas Market, No 1372, Discussion Papers of DIW Berlin from DIW Berlin, German Institute for Economic Research

Reeder, N., & Colantonio, A. (2013). Measuring impact and non-financial returns in impact investing: A critical overview of concepts and practice. The London School of Economics and the European Investment Bank Institute.

Reinartz, S.J., Schmid, T. 2016, Production Flexibility, Product Markets, and Capital Structure Decisions, The Review of Financial Studies, Volume 29, Issue 6, June 2016, Pages 1501–1548, https://doi.org/10.1093/rfs/hhv126

Ross, Stephen A.; Westerfield, Randolph W., Jordan, Bradford D. Fundamentals of corporate finance, 2nd Ed. Homewood, IL: Irwin Press, 1993

Rubinstein M. 2006. A History of the Theory of Investments . Hoboken : John Wiley & Sons

Smith, J. L., & Lee, T. K., 2017, The price elasticity of U.S. shale oil reserves. Energy Economics, 67, 121–135. https://doi.org/10.1016/j.eneco.2017.06.021

Statoil, 2013, Energy Perspectives 2013: Long-term macro and market outlook

Sundaram, A. K., & Inkpen, A. C. (2004). The corporate objective revisited. Organization science, 15(3), 350-363.

Temple, P., Urga, G., & Driver, C. (2001). The Influence of Uncertainty on Investment in the UK: A Macro or Micro Phenomenon? Scottish Journal of Political Economy, 48(4), 361–382. doi:10.1111/1467-9485.00204

Viviani, J. L., & Maurel, C. (2019). Performance of impact investing: A value creation approach. Research in International Business and Finance, 47, 31-39.

WEC, 2016, World Energy Resources: Unconventional gas, a global phenomenon, Report by World Energy Concil

WEC, 2019, Managing the Energy Transition, by World Energy Council, World Energy Issues Monitor 2019

Zhong, M., & Bazilian, M. D. 2018, Contours of the energy transition: Investment by international oil and gas companies in renewable energy. The Electricity Journal, 31(1), 82–91. doi:10.1016/j.tej.2018.01.001

Zingales, Luigi, 1998, Survival of the fittest or the fattest? Exit and financing in the trucking industry, Journal of Finance 53, 905-938.