Journal of Economics and Business 120 (2022) 106067

Contents lists available at ScienceDirect

Journal of Economics and Business

journal homepage: www.elsevier.com/locate/jeb

Investment choices and production dynamics: The role of price expectations, financial deficit, and production constraints

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ARTICLE INFO

Keywords:
Investment financing
Price expectations
Price elasticity
Energy supply
Technology

ABSTRACT

We propose a model that helps answer two questions: (1) what motivates firms to invest in novel technologies, often characterized by low (or negative) returns, forgoing high-profitability projects, and (2) why responses to price changes of seemingly similar firms may differ substantially. The developed framework reveals how financial limitations, production capacity constraints, and expectations on intertemporal price differences and productivity improvements alter investment decisions and the elasticity of supply. Using the U.S. unconventional oil and gas investment and production data, we reveal the trade-off between profit generation and investment-driven improvements in productivity. Then, with simulations, we show how the price elasticity of supply may differ across firms with different financial and production capabilities and how learning abilities and price expectations explain the negative elasticity (or "backward-bending" supply curve) phenomenon.

1. Introduction

Making investment decisions on technology and capacity choices, firms across different industries have to balance improvements in competitive advantage, financial performance, and sustainable production (Mizik & Jacobson, 2003). The adoption of new technologies, promising higher productivity and/or lower costs in the future, often first, requires financing of low or even negative profitability projects.[1] To untap the benefits of technological advances and economies of scale, firms may need to forgo profitable opportunities in the present (Deign, 2019). And though decisions considering "option time value" are not new, the complications related to constraints on projects capacity and time availability2 requiring to balance the exhaustion and the growth are often neglected (Mason & Roberts, 2018; Mason, 2001; Mason, Muehlenbachs, & Olmstead, 2015). Considering investments as an instrument to control future cost and production capacity, a firm can gain control over its supply as well as the response to *exogenous* price changes. Thus, the U.S. unconventional oil and natural gas industry, which motivated and inspired our research and analysis, has continued to grow its supply even in times of energy price drops. The observed negative supply elasticity phenomenon has been attributed to the rebalancing of the project portfolio and to investments that enabled the productivity improvements (Ikonnikova et al., 2018). Similarly, power companies reshape their portfolios by divesting from still-profitable (fossil energy) assets and investing in

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[1] For example, green hydrogen commercial production, or production from experimental long-lateral unconventional well developments.

[2] Renewable wind and solar projects vary in their generation potential or production capacity across geographical areas and are limited by the locations available for installation, especially onshore.

https://doi.org/10.1016/j.jeconbus.2022.106067
Received 30 March 2021; Received in revised form 1 April 2022; Accepted 4 April 2022
Available online 7 May 2022
0148-6195/

renewable technologies (often low or zero profitability) in a face of regulatory and price uncertainties suggesting some assets may not be used in the future (Reinartz & Schmid, 2016; Turner, 2009). In its turn, differences in views, e.g. on the future carbon-policy-related production constraints and the trajectory for technological efficiency, lead some automotive manufacturers to investing in new products, such as electric and fuel cell vehicle, before they prove to be profitable, while others remain hesitant weighing financial value against market potential (Gnann et al., 2018). While the climate change agenda brings similar considerations to the increased number of industries, other industries, like video game or pharmaceutical, traditionally face agility problems when making R&D investments (Giaccotto, Santerre, & Vernon, 2005; Pammolli, Magazzini, & Riccaboni, 2011). Empirical studies confirm the importance of financing considerations (Bolton, Wang, & Yang, 2019; David & Sibilkov, 2010); production flexibility (MacKay, 2003; Reinartz & Schmid, 2016); demand and price expectations (Fuss & Vermeulen, 2008); and regulatory and technological uncertainty (Kang, Lee, & Ratti, 2014; Miao, 2005). Yet, the focus on an individual issue rather than an entire combination of factors and their interplay gives rise to a diversity in insights and investment solutions, highlighting the need for a unified approach to support firms in their decision-making (Benaija & Kjiri, 2014; Campiglio, Kemp-Benedict, Godlin, & Matikainen, 2019; Campiglio, Kemp-Benedict, Godlin & Matikainen, 2017; CDP, 2019; WEC, 2019).

The purpose of our work is to link and align different views concerning investment choices and production dynamics (from investment theory to production and industrial economics), by explaining their empirical and theoretical diversity. To that end, we develop a firm behavior model that suggests (1) why and under what conditions firms forgo investments in apparently profitable projects and invest in projects with a negative expected return instead (e.g., divesting from fossil fuels and investing in alternative energy projects), and (2) what combination of investment drivers leads to a (temporal) negative elasticity of supply. Primary focus of our study is on the roles and interplay of financial and supply constraints; intertemporal project value; and learning and technological improvements effects.

Methodologically, our work relates to the literature on capital allocation, real options, and production dynamics. We combine the elements of investment theory and project portfolio selection models, highlighting the role of uncertainty, time delay, and project competition for the firm's financial resources (Abel, Dixit, Eberly, & Pindyck, 1996; Archer & Ghasemzadeh, 1999; Dixit & Pindyck, 1994; He & Pindyck, 1992). We study how firms allocate their budgets across projects (or resources and technologies) with different productivity, expecting that investing will improve future productivity. Furthermore, we take into account that the learning and technological advances' rates may differ across projects (and firms) and that some projects may have capacity constraints, limiting the firm's ability to invest in them altogether or in the future.[3] In this regard, we not only derive the optimal investment allocation based on the firm's budget but we also analyze how its financial constraints are intermingled with investments, through their influence in supply dynamics and productivity growth. Thus, our study contributes to the research on endogenous technological improvements, and production growth (Jin, Zhao, & Kumbhakar, 2019; Levine & Warusawitharana, 2021).

We highlight the connection between supply dynamics and project-choice dynamics, by considering a firm whose future production possibilities (assets) depend on its productivity-boosting investments and, hence, financial capabilities. Notably, the effect of project selection and resource exhaustion is rarely included explicitly in industrial economics and microeconomics models, especially in the context of the intertemporal financial constraint (Beviá, Corchón, & Yasuda, 2020; Caballero & Pindyck, 1996; Gomes, 2001). The few works that examine industry dynamics under financial constraints accounting for technological advances stop at the supply-analysis level, overlooking supply elasticity (Miao, 2005). We close this gap by deriving a general intuition from explicit functions of the elasticity of supply, and by showing how this elasticity may take both positive and negative values and change over time along with technologies and constraints.

We also focus on the role of firms' expectations regarding future prices and productivity improvements, by deriving the price elasticity of supply as a function of financial and capacity constraints. That links our study to works on "real options" (Smith & Nau, 1995; Pindyck, 2004; Thompson, Davison, & Rasmussen, 2009). Real options analysis highlight the "value of waiting" when advising on the optimal investment path. Existing studies include factors also brought into our analysis, such as future price changes, resource exhaustion, or financial constraints, and, in some cases, a combination of these (Mason, 2001; Obersteiner et al., 2002; Paddock, Siegel, & Smith, 1988; Reuter, Fuss, Szolgayová, & Obersteiner, 2012). Traditional real option models are often coupled with financial constraints and technological improvement assumptions but neglect investment-driven productivity improvements that may relax capacity constraints (Davis & Owens, 2003; Wei, 2015). Our work accounts for the fact that the differences in today's and tomorrow's returns depend not only on price changes but also on endogenous productivity changes, which can affect supply capabilities and price responses.

Besides understanding and advising firms on investment choices and timing, our work aims at deriving an elasticity of supply suitable for empirical verification. In this regard, our paper relates to the extensive body of empirical and applied studies on the extraction of natural resources, continuing the line of reasoning of Hotelling (1931). Although most studies concerned with optimal resource extraction mainly focus on production choices and exhaustion rates, some pay attention to the endogeneity of productivity and financial constraints (Chakravorty, Magne, & Moreaux, 2006; Chakravorty, Moreaux, & Tidball, 2008; Gaudet, Moreaux, & Salant, 2001; Kellogg, 2011). However, in supply-elasticity analyses, the endogeneity of production capacities and technological advances is often missing or treated exogenously (e.g., Dahl & Duggan, 1996; Krichene, 2002; Medlock, 2012; Arora, 2014; Ponce & Neumann, 2014; Hausman & Kellogg, 2015; Newell, Prest, & Vissing, 2019). A notable exception is the work by Smith and Lee (2017) that explores the nontrivial relationship of resource exhaustion, productivity dynamics, and the price elasticity of supply, revealing how

[3] The future use of natural gas, oil, and coal resources may be limited, resulting in stranded assets. On the other hand, wind and solar projects may be exhausted, as the producers run out of economically and technically suitable locations.

cost savings may outweigh the lost revenue, leading to a "backward-bending" supply curve. We build on this and similar findings (Mason & Roberts, 2018; Mason, 2001), by adding that the "option value for waiting" may differ across projects.

Understanding the supply consequences of investment decisions is critical for firms' resiliency. We assert that the results of our analysis are valuable to industry and government practitioners, who need flexible models (that could be expanded and updated) for their investment and supply strategy decisions, applicable to the complexity of the real world (CDP, 2019). In what follows, we start with a motivating example, laying the foundation for the investment model presented in Section 3. Then, we use the solution for the optimal investments to analyze the elasticity of supply analysis in Section 4. There, we provide theoretical insights complemented by numerical illustrative simulations, and we cite an example that ties our conclusions to the observations and motivation presented in Section 2. We conclude with a discussion of limitations, implications, and possible venues of the model for future research.

2. Motivation

In 2018, a data-driven study of U.S. unconventional natural gas resource development, based on more than a decade of production data from the horizontal Marcellus play natural gas wells, reported that producers systematically invest in projects with negative returns and may at times increase their production despite falling prices (Ikonnikova et al., 2018). The IHS Markit (2019) well-level data from the Marcellus play, combined with geologic resource characteristics and well-cost data, enabled researchers to examine production location choices and investment trends corresponding to the observed supply dynamics.

The IHS study concluded that although the drilling budgets were correlated to the natural gas prices, the aggregate play production had no apparent relationship to prices (Fig. 1, left plot). 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 financial results and the future price expectations.[4]

In addition, the analysis of the drilled well locations has revealed that in contrast to the classical investment theory, projects with negative expected present value, or a profitability index[5] smaller than 1, have been systematically included in the drilling portfolio (Fig. 2). The computations have also shown how the price elasticity of supply tends to decrease over time.

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 break even within 20 years under the fixed price assumption. This observation led to the following two conclusions: (1) producers are likely to make their investment decisions based on future (including hedging-based) price expectations and (2) a certain fraction of well 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.[6] However, the median well seems to break even, based on the short-term natural gas price outlooks in a corresponding year. When natural gas prices plummeted in 2015–2016 across all Marcellus play hubs, we saw a downshift of the corresponding profitability distributions (Fig. 2a).

The profitability index, with the profits proportional to the prices, allows for the following estimations: the median well with the profitability of $\sim$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 and reach the value of 1. By 2018, the year-average natural gas price in the Marcellus reached \$2.63/MMBtu, suggesting producers' expectations are likely to be met.[7] Similar observations and accompanying conclusions about the Haynesville and Eagle Ford plays have also been presented (Gülen et al., 2015; Ikonnikova, Male, Scanlon, Reedy, & McDaid, 2017). IEA (2020) also highlighted the variability in project returns (in aggregate) for the oil and gas industry.

The third finding relevant to 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 per-well production data reveal that productivity has been increasing over time, with high-resource-density areas exhibiting lower improvements than lower density areas. It has long been recognized that the technological progress of resource recovery in high-density locations has less room for improvement (Fisher et al., 1988). Productivity increases over time with experience, learning, and deployment of advanced equipment, all of which are driven by and require investments. The data analysis suggests a link between investment intensity and recovery efficiency, with some advances industry-wide and others firm-specific (Kellogg, 2011).

Boosts in productivity driven by investments and the effects of learning-by-doing, however, come at the expense of accelerated resource exhaustion, introducing or tightening supply constraints. 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 being the most commercially attractive (Fig. 2b). Over time, however, producers transition to investing in lower-resource-density locations, tapping into more abundant but commercially unattractive projects, and waiting for investments and technological advances to boost their productivity to become profitable.

Aligning price and location choice statistics, we find that investments in low-return projects occur in times of increasing price

[4] Similar findings are reported for other shale plays (Browning et al., 2013; Gülen, Ikonnikova, Browning, & Tinker, 2014, 2015).

[5] The profitability index is a ratio of the discounted future profits to the investment capital costs. It measures whether a project breaks even (value >1). Here, we assume that the price is fixed for the entire period.

[6] The "optimistic" price projection refers to the EIA's Annual Energy Outlook scenarios in the corresponding years.

[7] Our analysis includes data on natural gas wells only, disregarding oil wells drilled in the northwestern part of the Marcellus play, to limit the influence of oil prices on the analyzed drilling dynamics.

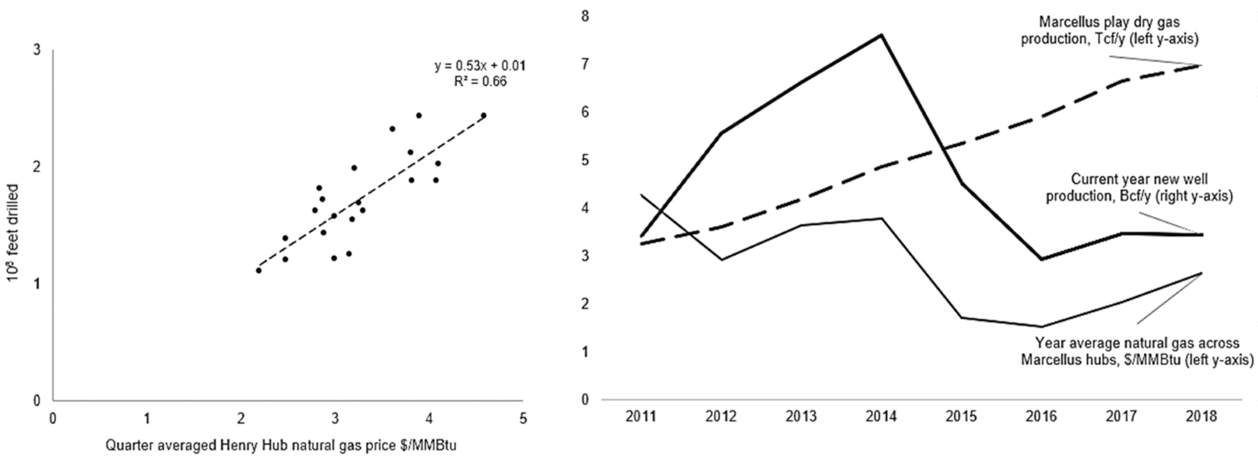

Fig. 1. Natural gas price and capital spending, approximated by feet drilled (left) and supply (right).

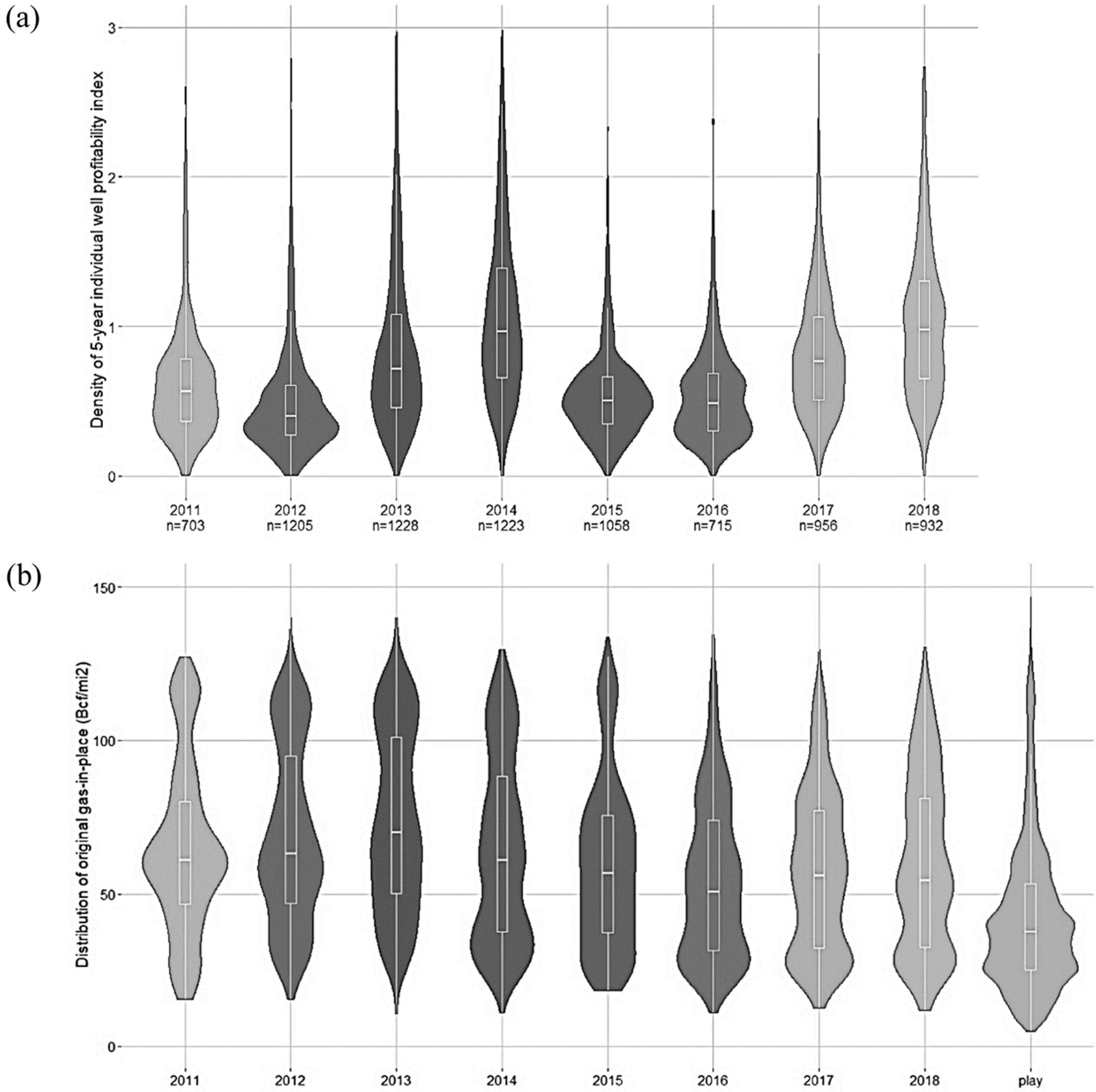

Fig. 2. Probability distribution plots for (a) the 5-year profitability index of Marcellus wells and (b) original gas-in-place at the well locations compared to the entire play (based on Ikonnikova et al., 2018).

expectations. In 2013–2014, almost 30% of developed locations were low-productivity sites, compared to in 2015, when only half as much capital was dedicated to lower-resource-density locations. As a result, productivity in the low-density areas shifted upward in 2014, and also in 2017, the year when prices recovered and the future suggested further increases.

Combining financial estimates with historical price dynamics[8] and distinguishing between the legacy (existing by the beginning of a new year) and incremental new-well production, we find the evidence of negative price elasticity of supply (Table 1).

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 wells' total 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 negative result suggests that positive expectations (e.g., improvements in technological efficiency) may outweigh the price signals in the growth stage. In contrast, in late life, the negative elasticity can be explained by debt buyouts and the necessity for paying dividends, thus reducing the funds available for reinvestment. Hence, we find that the cash flow elasticity of investments is positive.

Investing in seemingly uneconomic projects, leading to the negative elasticity of supply, is not limited to the unconventional oil and gas production industry. In the context of low-carbon transition, companies in other industries worldwide, especially in Europe, have been increasing shares of new technologies in their portfolios. Thus, power and chemical industry companies have been investing in alternative resources, such as hydrogen, although such alternatives have not yet proven to be economically viable (Chapman, Itaoka,

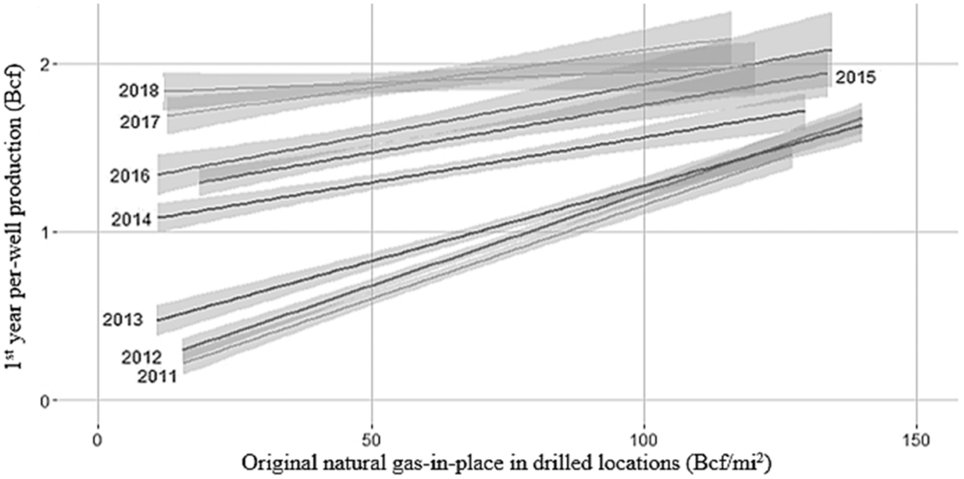

Fig. 3. Trend lines with 95% confidence intervals (shadowed) for the changes in per-well first-year natural gas production.

Table 1
Price elasticity of Marcellus natural gas production.

Production year	Marcellus NG price ($/MMBtu)	Price elasticity of total production	Price elasticity of well supply
2011	4.27		
2012	2.91	-0.27	-1.25
2013	3.63	0.68	0.81
2014	3.78	3.69	3.38
2015	1.71	-0.13	0.68
2016	1.53	-0.86	3.71
2017	2.03	0.41	0.58
2018	2.63	0.19	-0.10

Farabi-Asl, Fujii, & Nakahara, 2020). Automotive manufacturers have been expanding their portfolios with electric vehicles despite reports of unprofitable sales (Baik, Hensley, Hertzke, & Knupfer, 2019). The U.S. has also witnessed negative price elasticities in the timber industry, where between 2010 and 2017 the decreasing price dynamic was accompanied by increased production (Howard & Liang, 2018). Recognizing a variety of explanations and rationales for the observed industry behavior, including behavioral finance, security of supply, and reputation-related arguments, in our 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 returns, thereby forgoing high-return alternatives, and to analyze how such investment behavior determines supply dynamics, namely, the negative elasticity phenomenon.

3. The investment model

In this section, we analyze how an individual firm makes its investment choices, given financial and production-capacity constraints. We examine which projects a firm may choose, including its expectations about output prices and improvements in productivity through learning-by-doing and using technological advances. We start by defining the firm's value, including profit and asset value, and then we present the investment solution and a discussion of its rationale. Understanding a firm's investment behavior is critical to explaining production dynamics and the price elasticity of supply, analyzed in Section 4.

3.1. Firm's value

Consider a firm having some resources, or patents for technologies, the development of which we will call "projects," distinguishing them by index $l \in L$. Each project is characterized by its productivity or production per unit of capital q_t^l; because productivity may improve over time, we use subscript t. Then, multiplying productivity by the capital k invested, we obtain the total quantity produced by a given project, $Q_t^l = q_t^l k_t^l$, which is sold at market price, p_t. Productivity allows estimating a project's break-even cost and calculating profitability per unit of investment or a net price, p_t^l, such that $\frac{\partial p_t^l}{\partial p_t} = 1$. Each project's profit, π_t^l is defined by the product of its output, Q_t^l and its *net* price, p_t^l.

Profit Function In assessing its investment choices, a firm estimates its total profit by calculating:

$$\Pi_t = \sum_{l\in L} \pi_t^l = \sum_{l\in L} p_t^l Q_t^l = \sum_{l\in L} p_t^l q_t^l k_t^l \tag{1}$$

Assuming that the final output from all the projects is the same, for example, natural gas or some form of energy, p_t is the same for all the projects, and p_t^l varies due to productivity differences only. We also take a simplifying assumption: all the profit can be realized in one period only, in which the prices are fixed at the beginning of production, or it is defined by some fixed and known price profile, such as the one determined by a long-term contract.

Asset Value At period t, a firm knows p_t with certainty, but prices in later periods are unknown. However, the firm has expectations about the future price path, combined into $\widehat{p}_{t+1}$ and translated into the project-specific net price $\widehat{p}_{t+1}^l$. Then, applying a project-specific discounting $\gamma_t^l \leq 1$, capturing various (regulatory) uncertainties and idiosyncratic risks, a firm can estimate the value its resources have left for future development, or it can consider them for divestment as:

$$A_t = \sum_{l\in L} \gamma_t^l \widehat{p}_{t+1}^l \overline{Q}_{t+1}^l = \sum_{l\in L} \gamma_t^l \widehat{p}_{t+1}^l \cdot \left(\overline{Q}_t^l - Q_t^l\right) \cdot \tau_t^l \tag{2}$$

Asset value A_t can also be seen as a present value or liquidation value, as suggested by Mello and Parsons (1992). Yet, we expand (2) to compare to other works in two important aspects: we explicitly incorporate resource limitation or production capacity $\overline{Q}_t^l$, reduced to $\overline{Q}_t^l - Q_t^l$ by the end of the period, and allow for productivity improvements captured by the technology multiplier $\tau_t^l \geq 1$. We recognize two channels for an increase in productivity: industry-wide technological advances, with $\alpha \geq 1$ and the investment dependent learning-by-doing effect, denoted $\beta \geq 0$, with $\tau_t^l = \alpha + \beta k_t^l$. Technological advances and learning abilities may vary across projects and may be resource- or firm-specific, in which case:

$$\overline{Q}_{t+1}^l = \left(\overline{Q}_t^l - Q_t^l\right) \cdot \left(\alpha_t^l + \beta_t^l k_t^l\right) \tag{3}$$

Yet, for the sake of notational simplicity, in the following, we allow for similarity in expectations about technological parameters, namely $\alpha_t^l = \alpha$ and $\beta_t^l = \beta$, unless marked otherwise.

Production Capacity and Financial Constraint Substitution of Eq. (3) into Eq. (2) reveals a crucial trade-off faced by the firm: invest more to improve future productivity and return on investments or spare the production capacity for the future and enjoy industry-wide advances. We illustrate that trade-off in Fig. 4, showing how at lower levels of investments the technological benefits may predominate, leading to an increase in the remaining production capacity. However, more aggressive investment would exhaust capacity faster, precluding the increases in productivity from replenishing capacity (Appendix 1).

Although production capacity constraints may be linked to exhaustion in the case of natural resources, in terms of technology patents or other projects, one may think about the exhaustion of physical spaces, e.g., locations for wind turbines and solar farms, consumption possibilities, e.g., of vehicles per person, time, or other limitations. In either case, one may show how improved productivity helps relax production capacity constraints, which we can also express in investment terms, where $\overline{K}_t^l = \overline{Q}_t^l / q_t^l$ is the ultimate amount of capital needed to exhaust the project completely. In reality, we find numerous examples, including those discussed in the previous section, of production being constrained not only by capacity but also by the financial resources of a firm. To that end, we introduce investment capital or financial constraint $\varepsilon_t \bullet \overline{\Pi}_t$, where $\overline{\Pi}_t = \sum_{l\in L} p_t^l \overline{Q}_t^l$ is the maximum profit, or collateral, the firm may get, and ε_t is a time-varying financing multiplier capturing the firm's ability to raise external capital and/or obligations on dividends.[8] Clearly, when production capacity is small, a firm may not experience financial limitations, whereas in the face of vast production possibilities, a firm may not be able to realize all of them due to the financial constraint.

Firm's Value and Investments According to the classical Modigliani-Miller definition,[9] the value of a firm consists of its profits, Π_t and the present value of assets, A_t:

$$V_t = \Pi_t + A_t \tag{4}$$

A rational risk-neutral firm,[10] having the market price knowledge and price expectations described above, would invest in available projects so as to maximize its total value, V_t. In doing so, the firm takes into account both production capacity (PC) and financial constraints (FC). Thus, formally, we define the firm's investment decision model as:

$$V_t = \sum_{l\in L} p_t^l q_t^l k_t^l + \sum_{l\in L} \widehat{p}_{t+1}^l \left(\overline{Q}_t^l - q_t^l k_t^l\right) \cdot \left(\alpha + \beta k_t^l\right) \{k_t^l\}_{l\in L} max \tag{5}$$

$$\text{FC} : \varepsilon_t \cdot \overline{\Pi}_t - \sum_{l\in L} k_t^l \geq 0 \text{ and PC} : \overline{K}_t^l - k_t^l \geq 0$$

[8] In general, the multiplier depends on various factors, including the value of assets and cost of capital, but those considerations are beyond the scope of our analysis. Here we rely on insights from Ross, Westerfield, and Jordan (1993).

[9] See Modigliani and Miller (1958).

[10] The assumption of risk neutrality does not limit the generality of our analysis, but it helps keep the analysis straightforward. Alternatively, a corresponding correction of the discounting factor could be applied.

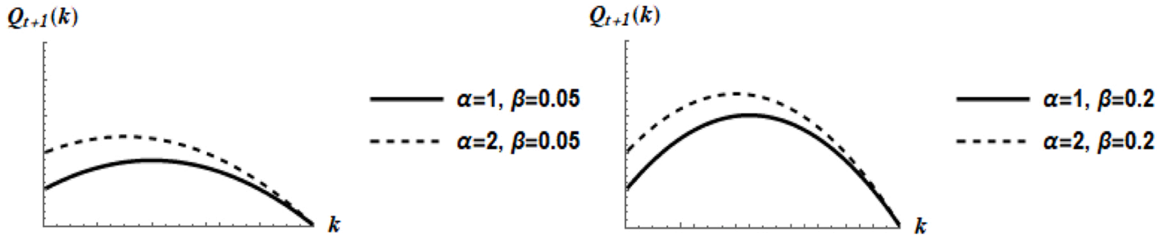

Fig. 4. Production capacity as a function of investments and productivity-improvement parameters.

The investment problem (5) features the two interrelated constraints and drops the commonly used profit non-negativity condition. Non-negativity is critical in developing the understanding as to why and how much firms invest in projects with negative return. To illustrate this idea, consider the case of a novel (clean energy) technology with low productivity (Fig. 5).

The immaturity of the technology suggests that investment in such a project may result in negative profit. However, the firm may gain some important knowledge and experience, thereby improving the project's economics in the next period. In this case, the anticipation of a positive future profit is captured by the positive and increasing asset value function. For as long as today's a-la R&D investments are outweighed by the expected future profit considerations, a firm's investment strategy is justified.

By investing, the firm balances the increase in its value through profit and asset value. Asset value and the differences in production capacities may help explain other puzzles, such as investments in low- instead of high- return projects (Fig. 6).

A firm choosing between two projects with $q^{low} < q^{high}$ may prefer investing in a *low*-productivity project to prevent the exhaustion of a *high*-productivity project and to learn how to boost the productivity and profitability of its plentiful asset. However, a financially constrained firm may not have all the same choices as an unconstrained firm, suggesting why firms with the same investing opportunities would make different investments. To develop further intuition on why and how firms' strategies vary and change over time, we proceed to solve (5) formally.

3.2. Optimal investment choice

Solving the investment optimization problem, defined by (5), requires the Lagrangian and Kuhn-Tucker conditions, which lead us to distinguishing three cases[11]:

1. Unconstrained Case (UC): The firm is unconstrained in its financial capabilities or has enough capital to develop any available project optimally, so that neither PC nor FC is binding.
2. Financially Constrained Case (FC): The firm's financial situation prevents it from developing the desired projects optimally, and it has to ration its capital, choosing suboptimal levels of investments.
3. Capacity Constrained Case (CC): A firm may or may not have ample financial resources, but it cannot invest the *chosen* projects optimally due to capacity constraints; i.e., production capacity (PC) for some projects is binding.

We name case 2 by the financial constraint, which it determines. However, to emphasize that case 3 may be characterized by PC alone or by the combination of FC and PC, we name it differently from PC. We start with the unconstrained case analysis to investigate how the constraints affect investment choices and to help explain production dynamics. Next we present the solutions and discuss the intuition behind them, relegating the technical details to Appendices 2 and 3.

Unconstrained Choice In case neither constraint is binding, optimal investments are:

$$k_t^{l\,UC} = \frac{p_t^l}{2\beta\gamma_t^l \widehat{p}_{t+1}^l} - \frac{\alpha}{2\beta} + \frac{\overline{Q}_t^l}{2q_t^l} = \frac{\left(\rho_t^l - \alpha\right)}{2\beta} + \frac{\overline{K}_t^l}{2} \tag{6}$$

where $\rho_t^l = \frac{p_t^l}{\gamma_t^l \widehat{p}_{t+1}^l}$ can be interpreted as the project's intertemporal opportunity cost, measuring the trade-off between today's versus tomorrow's production value, and highlighting the role of the discounting factor. As intuition dictates, we find that the bigger the possible losses from a given project, i.e. the smaller $p_t^l < 0$, the less money the firm will invest in l. If the net price $p_t^l < 0$ and the discounted future net price is such that $\rho_t^l \le 1$, then $1 - \alpha \le 0$. In this case, we find that investments increase in β besides, depending positively on the production constraint $\overline{K}_t^l$.

In contrast, high uncertainty and lower future price expectations would suggest $\rho_t^l \gg 1$, e.g., in the case of risk for a stranded resource $\gamma_t^l \widehat{p}_{t+1}^l \to 0$. Then, an increase in β would make the first summand in (6) smaller and hence, investments decrease. Thus, we

[11] We look at these possible situations with respect to the constraints. Note that both FC and PC cannot be binding at the same time, as one may proof substituting one into the other.

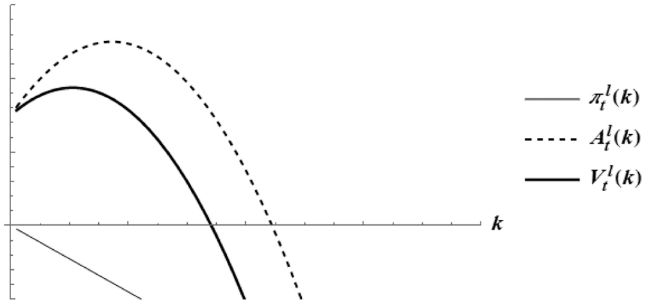

Fig. 5. Interplay of a firm's profit, asset, and value in case of a negative return (a-la R&D) project.

arrive at a curious result, suggesting that a firm's learning ability, β may have both a positive and a negative impact on investments, depending on the intertemporal project value. Uncertainty about the future value, or risk of inability to exploit production capacity in the future, destroys the value of learning and induces the firm to produce more today. Low risk and a high technological spillover effect could lead to making fewer investments today and instead to adopt "waiting" as a preferred strategy. In the case of $\frac{(\rho_t^l-\alpha)}{\beta} \to 0$, i.e., when opportunity cost is balanced by expectations on industry-wide improvements, α, or when learning ability is extremely high, investments are determined by production capacity alone.

In summary, we find that expectations on investment-driven productivity improvements help explain the variety of possible investment outcomes beyond those suggested by production capacity constraint (resource exhaustion) or "option value of waiting" individual literature strands (Majd & Pindyck, 1987; Mason, 2001; Smith & Nau, 1995). Excluding uncertainty and investment-drive technology from consideration, we find that investments are governed solely by PC and price expectations. Comparing the results across projects, we determine that ceteris paribus the firm invests more in projects with greater capacity or with the greater net price advantage.

Our insights also differ from those from classical Hotelling (1931) resource extraction problems, which stipulate that resource producers are motivated by profit and suggest that the closer the firm is to the exhaustion of a given resource, the less it invests in a given project. Including asset value and allowing for endogenous productivity growth, we provide an argument for production growth despite resource exhaustion. On the other hand, we establish that the intertemporal expected value difference and technology expectations may motivate the firm to withhold from investments completely. This conclusion explains why some resources, such as coal mines or the shale gas plays, are abandoned before complete exhaustion. We summarize the above results in:

Corollary 1. *(UC): The unconstrained firm will*

- *invest in projects with* $\frac{p_t^l}{\widehat{p}_{t+1}^l} > \alpha\gamma_t^l$, *with* $k_t^{l^{UC}} = \frac{1}{2\beta}\left(\rho_t^l - \alpha\right) + \frac{\overline{K}_t^l}{2}$ or.
- *forgo investments if* $\rho_t^l \le \alpha - \beta\overline{K}_t^l$ *or if* $p_t^l \le \gamma_t^l \widehat{p}_{t+1}^l$ *under* $\alpha = 1$ *and* $\beta = 0$.

To solidify the intuition behind the UC analysis, we offer a graphical illustration of how investments change with an increase in today's market price (Fig. 7). The solid black line is drawn under the same parameter values for all four plots, and it serves as a reference for cross comparison. Keeping the values of break-even cost and the discounting factor fixed, we alter productivity improvement parameters, production capacity, and expected future price values.

These plots show how an increase in the industry-wide improvements induces the firm to invest less today. The ability to increase productivity through β could have a positive as well as a negative effect on optimal investments, depending on price expectations. Anticipation of future price reduction incentivizes the firm to invest more, whereas a higher price tomorrow incentivizes waiting. This observation lays the foundation for the negative elasticity phenomenon explained in the next section.

Financially Constrained Choice In cases where optimal investments exceed the budget, $\sum_{l\in L} k_t^{l^{UC}} > \varepsilon_t \cdot \overline{\Pi}_t$, and the firm is unable to realize all projects optimally and must decide how the limited financial resources are rationed. The binding FC leads to the solution with the shadow cost of financing measured by the Lagrange multiplier equal to $\frac{\partial V_t}{\partial k_t^1} = .. = \frac{\partial V_t}{\partial k_t^L}$. This implies that incentives to invest are equalized across the projects, as discussed in Appendix 3.

We formulate the financially constrained solution (7) in terms of the unconstrained investment to highlight the rationing multiplier η_{t+1}^l. It shows how the financing deficit δ_t, namely the difference between what the firm wants to invest and what it can invest, is distributed among the projects:

$$k_t^{l^{FC}} = k_t^{l^{UC}} + \eta_{t+1}^l \cdot \left(\varepsilon_t \bullet \overline{\Pi}_t - \sum_{m\in L} k_t^{m^{UC}}\right) = k_t^{l^{UC}} - \eta_{t+1}^l \cdot \delta_t \tag{7}$$

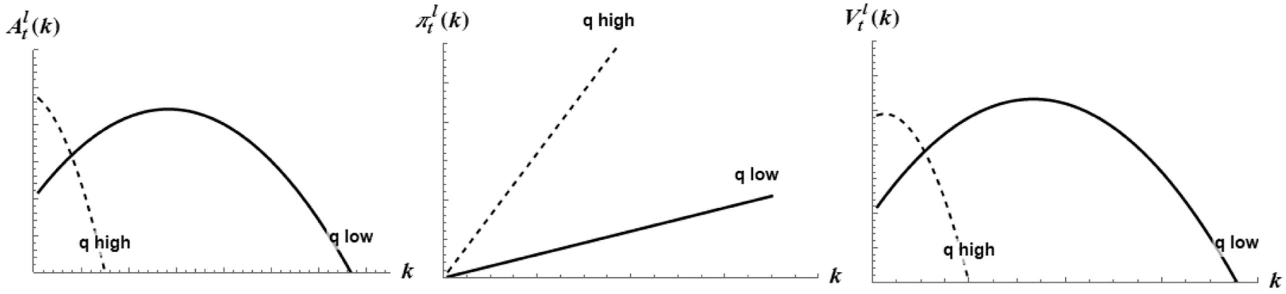

Fig. 6. Differences in asset values may explain a firm's preference for low- over high-return projects.

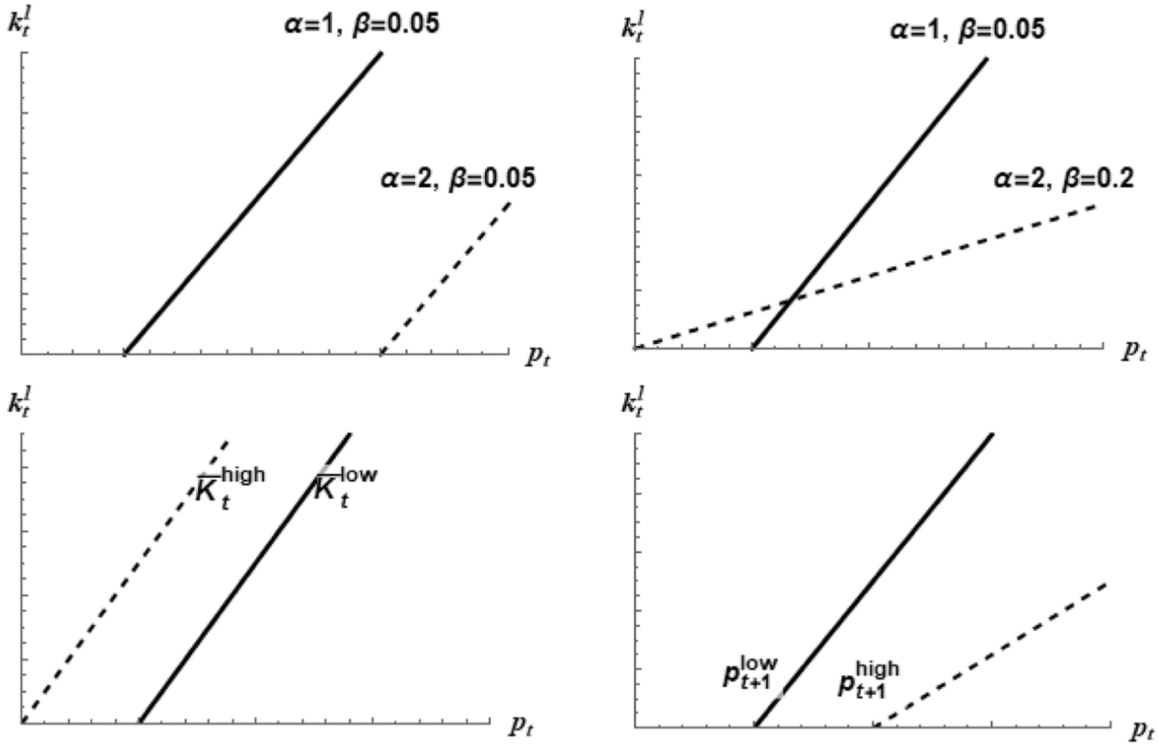

Fig. 7. Effects of technology, price expectations, and production capacity on UC investments.

$$\eta_{t+1}^l = \frac{\widehat{\pi}_{t+1}^l}{\sum_{m \in L} \widehat{\pi}_{t+1}^m} = \frac{\gamma_t^l \widehat{p}_{t+1}^l q_t^l}{\sum_{m \in L} \gamma_t^m \widehat{p}_{t+1}^m q_t^m} \tag{8}$$

Thus, by $\widehat{\pi}_{t+1}^l$ we denote the profit that the firm would get if, instead of investing today, it invests one unit of capital tomorrow, marketing the resultant production $1 \cdot q_t^l$ at price $\widehat{p}_{t+1}^l$. Then, η_{t+1}^l represents the weight of an individual project's expected value within the expected value of all the projects if they had been invested with a spared unit of capital tomorrow. The rationing term $\eta_{t+1}^l \cdot \delta_t$ includes q_t^l rather than q_{t+1}^l because shifting investments to tomorrow precludes productivity improvement.

Thus, we determine that the optimal investment profile is adjusted based on the "value of waiting" or investing tomorrow: the firm cuts financing more for projects that have a higher return tomorrow. Projects with the same expected return are rationed proportionally to their productivity: $\frac{\eta_{t+1}^l}{\eta_{t+1}^m} \rightarrow \frac{q_t^l}{q_t^m}$. With the future net prices and productivity being the same, rationing is governed by the associated risks, γ_t^l. We combine those results into:

Corollary 2. *(FC Case): A financially constrained firm would allocate its funds by reducing the amount invested relative to the unconstrained optimum, based on the expected project's profitability, rationing the projects with a higher future net price more than the other projects.*

Fig. 8 shows the effects of financing deficit and of changes in the expected project's value on investment, $k_t^{l\,FC}$. To draw attention to a

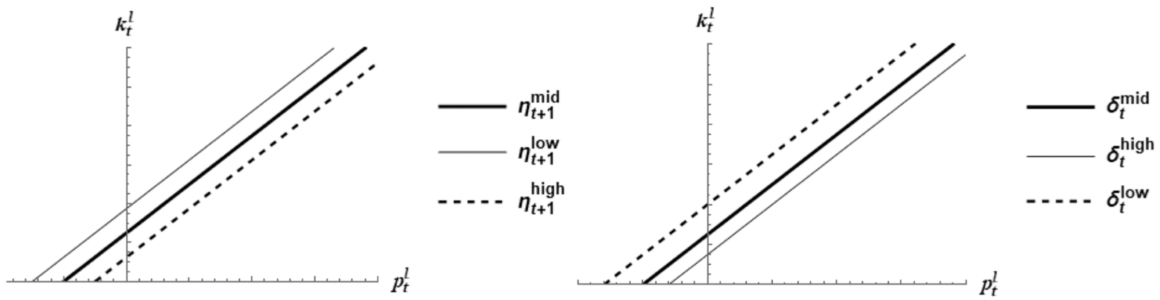

Fig. 8. Effects of the rationing term and financial deficit on investments.

project that may have a negative return in period t, we plot p_t^l for on the x-axis and show the optimal investment level when $p_t^l < 0$ and therewith, $\rho_t^l < 0$ for all $\widehat{p}_{t+1}^l \geq 0$. Resulting from Eqs. (7) and (6), $k_t^{l^{FC}}$depends linearly on current return, with investments being positive even for the negative-return-value projects. Although both rationing term η_{t+1}^l and the financial deficit δ_t affect the vertical shift or intercept value for $k_t^{l^{FC}}$-line, we want to emphasize the difference in their meanings and show them on separate plots. The left plot shows how the higher project's return in the future results in greater rationing or lower investments today. On the other hand, the lower the deficit is, the higher the investments are, even with decreasing in net (or absolute) future expected price.

We conclude with an interesting observation that investments may fall due to (1) an increase in the project's expected future value or (2) a decrease in the current price. Had the productivity stayed the same, one might expect a negative change in production despite the increase in today's prices, owing to the changes in the future expected values or financial deficit. Whereas statistical models often capture that phenomenon with fixed or random effects, our model provides tangible intuition and suggests how and why the empirical observations could vary over time.

Capacity Constrained Case Finally, we consider the investment solution when PC is binding. First, we have to recognize that capacity constraints may not be binding for all the projects, e.g., for projects with $\frac{p_t^l}{\widehat{p}_{t+1}^l} < \alpha\gamma_t^l$: if $\alpha\gamma_t^l \to 1$ and $p_t^l < \widehat{p}_{t+1}^l$, then $\forall l : k_t^{l^{UC}} \leq \frac{\overline{K}_t^l}{2}$. However, in the case $\rho_t^l - \alpha > 0$, PC may become binding. Limiting the production and the assignment of financial funds, PC may relax FC, reducing δ_t and, as a result, increasing $k_t^{l^{FC}}$for which $k_t^{l^{UC}} < \overline{K}_t^l$. Formally, CC case investments are determined by:

$$k_t^{l^{CC}} = min\left[\overline{K}_t^l, k_t^{l^{UC}} + \eta_{t+1}^l \cdot \left(\varepsilon_t \bullet \overline{\Pi}_t - \sum_{m\in L} min\left[\overline{K}_t^m, k_t^{m^{UC}}\right]\right)\right] \quad (9)$$

Despite the obvious similarity between FC and CC cases, one must recognize an important distinction: the inability to invest in some projects optimally due to PC may let the firm invest in other projects optimally, without rationing, or help the firm reduce the need for rationing. Formally, we conclude with:

Corollary 3. *(CC Case): A firm whose investments in some projects are limited, owing to a production capacity constraint, will:*

- *invest optimally in all other projects if* $\varepsilon_t \bullet \overline{\Pi}_t \geq \sum_{m\in L} min\left[\overline{K}_t^m, k_t^{m^{UC}}\right]$ or.
- *increase financing (or reduce rationing) of projects*$k_t^{l^{CC}} > k_t^{l^{FC}}$ *not limited by PC using the released* $\sum_{m\in L} k_t^{m^{UC}} - \sum_l min\left[0, \overline{K}_t^l - k_t^{m^{UC}}\right]$ *funds.*

In other words, considering PC explains why some projects receive more financing: $k_t^{l^{CC}} > k_t^{l^{FC}}$. Taking production capacity constraints into account helps explain why firms with an apparent financing constraint may perform as unconstrained with respect to their investments in some projects. In the elasticity analysis (Section 4), we focus on UC and FC cases, but we also discuss the implications of CC.

3.3. Implications for adoption of new technologies

The two major questions motivating our study have been (1) why firms invest in projects with expected negative return, limiting their investments in profitable projects; and (2) why firms facing similar investment choices make different decisions. The analysis presented in this section provides several rationales for such puzzling behavior. Firms without financial or production capacity constraints are prone to invest:

- in technologies or projects with negative returns, expecting improvements in productivity and (possibly) an increase in production capacity, resulting in a firm's higher value and future returns thanks to learning (the higher the expected learning β, the larger the investments),
- in mature projects, to enjoy high profits, unless they expect that "waiting" has a higher value,
- in a combination of novel and mature projects driven by their production capacity $\overline{K}_t^l$ and the future price expectations balancing the "profit today" against "profit tomorrow."

Our model emphasizes that a firm may see the return on investments as consisting of two parts: the generated profit, and the asset value. Asset value increases as productivity improves, production capacity grows, or future prices rise. Keeping all things equal, investments into projects with higher profitability and production capacity would be larger. But a firm might prefer a project with negative return, if the project has a greater production capacity than a project with a positive return, or if the future ability to exploit the profitable project is limited (such as in the case of fossil fuel energy). For instance, the more intensively that renewable energy projects are developed, the higher the firms' ability to reduce their costs and to improve productivity per unit of land, thereby relaxing the production capacity constraint. However, as projects' economics improve, i.e., the net price increases to $p_{t+\Delta}^l \geq 0$, such projects could slow down development. Financially unconstrained firms could select a portfolio with a larger share of commercially unattractive projects and a smaller share of highly profitable projects. Balancing their positive financial performance and future returns (determined by the improvements in productivity and expansion of production capacity) can optimize their intertemporal return on investment.

Our results highlight the interplay of price expectations, productivity improvements, and production capacity constraints. In context of the ongoing energy transition, the risk of the inability to produce fossil fuels in the future would encourage firms to produce more resources today, leading to a so-called *green paradox*. On the other hand, the uncertainty would reduce the role of price expectations and make the role of production capacity more pronounced, thus intensifying the development of R&D-type projects, such as renewable energy generation, with almost unlimited production capacity.

For firms experiencing financial deficits, which prevents them from realizing all the desired projects at their optimal scale, we show how the intertemporal considerations are also used to ration the limited funds. We find that firms with financial deficits might need to

- reduce their investment relative to the unconstrained case, cutting the funding of options with the greater expected future return more
- allocate less capital to higher productivity projects if other risks and net prices are the same
- ration lower risk $\gamma_t \rightarrow 1$ projects more, saving them for the future, given that prices stay the same and productivity changes similarly across all the projects
- reconsider the value of its financial deficit and investment rationing, if there are projects affected by the production capacity constraint.

Thus, when deciding which project gets less financing, the firm must compare today's returns across its projects with the returns from investing in the projects tomorrow. The firm might spare the projects, which, if deprived of today's profit due to the investment cut, would compensate with higher profits in the future.

In summary, this model provided us with enough insights to understand our empirical observations. The analysis in the next section — elasticity or production dynamics in response to price changes — focuses on the UC and FC cases, addressing the PC case's outcome in the accompanying discussion.

4. Elasticity of supply as a function of investments

Throughout our analysis, we emphasize the role of current and future net prices and the constraints, both of which are expressed in terms of capital. In this section, our goal is to show how the elasticity of supply may change owing to changes in several factors determining a firm's investments. We are especially interested in deriving how the elasticity may be affected by productivity improvements and, hence, may vary with learning ability. To support this understanding, we conclude this section with simulations showing some possible production dynamics.

We start by relating an individual project's production to its total supply elasticity. One can also see this as a link between individual firms' and the total industry's price responses. Total supply comprises individual projects outputs, $Q_t = \sum_l Q_t^l$. Introducing a production share, $s_t^l = \frac{Q_t^l}{Q_t}$, we rewrite the classical point definition of elasticity as:

$$\epsilon = \frac{\sum_{l \in L} dQ^l}{Q} \cdot \frac{p}{dp} = \sum_{l \in L} s^l \left[\frac{p}{dp} \cdot \frac{dQ^l}{Q^l} \right] = \sum_{l \in L} s^l \cdot \epsilon^l \tag{10}$$

Our investment model from the previous section suggests that supply is a function of investment capital and productivity; therefore,

$$\epsilon^l = \frac{dQ^l}{dp} \cdot \frac{p}{Q^l} = \frac{p}{Q^l} \cdot q^l \cdot \frac{dk^l}{\partial p^l} = \frac{p}{k^l} \cdot \frac{dk^l}{dp} \tag{11}$$

Traditionally, economic studies consider a short-term or long-term price elasticity, focusing on producers' ability (and speed) to react and the set of options available to them. In our model, we allow producers to realize the same projects at any point but consider how constraints and parameters may change over time. Therefore, our elasticity analysis focuses on how the optimal investments, which are a function of the current and expected future net and, therefore, market prices: $k_t^l f(p_t, p_{t+1})$, react to the changes in those two prices. Mathematically, under the assumption that p_t is independent of p_{t+1} and vice versa, investments react as:

$$dk_t^l = \frac{\partial k_t^l}{\partial p_t} dp_t + \frac{\partial k_t^l}{\partial p_{t+1}} dp_{t+1} = dk_{t,t}^l + dk_{t,t+1}^l \tag{12}$$

$$\epsilon_t^l = \epsilon_{t,t}^l + \epsilon_{t,t+1}^l \quad and \epsilon_t = \epsilon_{t,t} + \epsilon_{t,t+1} \tag{13}$$

We find that the total price elasticity consists of two parts, the response to the current price and the response to future price expectations. We refer to (13) as the *total* elasticity, calling its two components the *price* elasticity and the future price *expectations* elasticity. Note that if only p_t or p_t^l changes while the expectations remain the same, then $\epsilon_t = \epsilon_{t,t}$. Alternatively, the firm may react only to the future (market and or net) price expectation changes, with $\epsilon_t = \epsilon_{t,t+1}$. Otherwise, the nontrivial results for the total elasticity stem from the fact that optimal investments, and hence production, are a linear function of net (and market) prices, but they depend inversely on price expectations.

In what follows, we investigate what affects the price elasticity, and analyze the total elasticity, focusing on the role of price expectations, moving all technical details and cumbersome derivations to the Appendix.

4.1. Price elasticity

The previous section's analysis has shown how the relationship between investments and prices alters when FC and PC are binding. Price response or the elasticity of production is, therefore, also affected by financial or production capacity situations. Thus, we derive the elasticity in the UC and FC cases, referring to the results in the previous section.

Unconstrained Elasticity We start with the "unconstrained" supply reaction to a change in the market price, p_t, and by substituting (6) into (11), we derive:

$$\epsilon_{t,t}^{l\ UC} = \frac{p_t}{k_t^{lUC}} \cdot \frac{1}{2\beta_t^l \hat{p}_{t+1}^l} \wedge \epsilon_{t,t}^{UC} = \sum_{l \in L} \frac{p_t s_t^l}{p_t^l + \hat{p}_{t+1}^l \left(\beta_t^l \overline{K}_t^l - \alpha_t^l\right)} \quad (14)$$

Expression (14) reveals that projects with different net prices, capacities, and other parameters may react differently to price changes. Thus, pessimistic firms with lower $\hat{p}_{t+1}^l$ could be more reactive with higher $\epsilon_{t,t}^{l\ UC}$. Project capacity with nearly endless capacity $\overline{K}_t^l$ may keep their production levels virtually unchanged, with low $\epsilon_{t,t}^{l\ UC}$, unless $\hat{p}_{t+1}^l$ and β_t^l values suggest otherwise. Examining individual project elasticities, we notice that innovative firms, with high β, might be less reactive. In contrast, firm that rely on high industry-wide technological advance, α, will change production more aggressively.

Rather than focusing on the shape of the price elasticity, which is a decreasing function of price, we focus on how the position of the elasticity line changes owing to differences in production capacity values, net prices, and productivity improvements parameters. We plot how the reviewed parameters may affect the individual project elasticity of supply depending on the market price, p_t, which represents the net price (market price minus break-even cost) (Fig. 9).

Fig. 9 elicits several interesting insights. First, we notice that at higher price levels, the changes in the listed parameters have a diminishing effect on the elasticity value, which becomes a near-constant. This probably explains the success of the studies that estimate elasticity as a constant. However, the assumption of constant elasticity may fail under low price values. Thus, we find that the impact of learning is nontrivial: high β values lead to a positive link between price and elasticity, whereas low β results in a negative link. The ability to learn and improve productivity endogenously helps to grow the future profit potential and hence be less sensitive to price. At low β, the firm exhausts its capacity faster than it expands, losing its ability to react to price or to extract the profit in the future. Although these results are not new, our approach brings them together in relation to price elasticity.

Constrained Elasticity Including financing deficit, we turn to (7) and focus on the effect that a price change has on the rationing term. The difference between UC and FC investments also results in the supply difference: $Q_t^{UC} - Q_t^{FC} = \delta_t \sum_{l \in L} \eta_{t+1}^l q_t^l$. So, in addition to the elasticity of the rationing term, we update the project's shares, s_t^{lFC}. With the UC results at hand, here we focus on the difference the financial constraint makes in the firm's reaction, deriving:

$$\epsilon_{t,t}^{FC} = \sum_{l \in L} \frac{Q_t^{UC}}{Q_t^{FC}} \cdot s_t^{l\,UC} \epsilon_t^{l\,UC} \left[1 + \frac{\left(Q_t^{UC} - Q_t^{FC}\right)}{\delta_t q_t^l}\right] \quad (15)$$

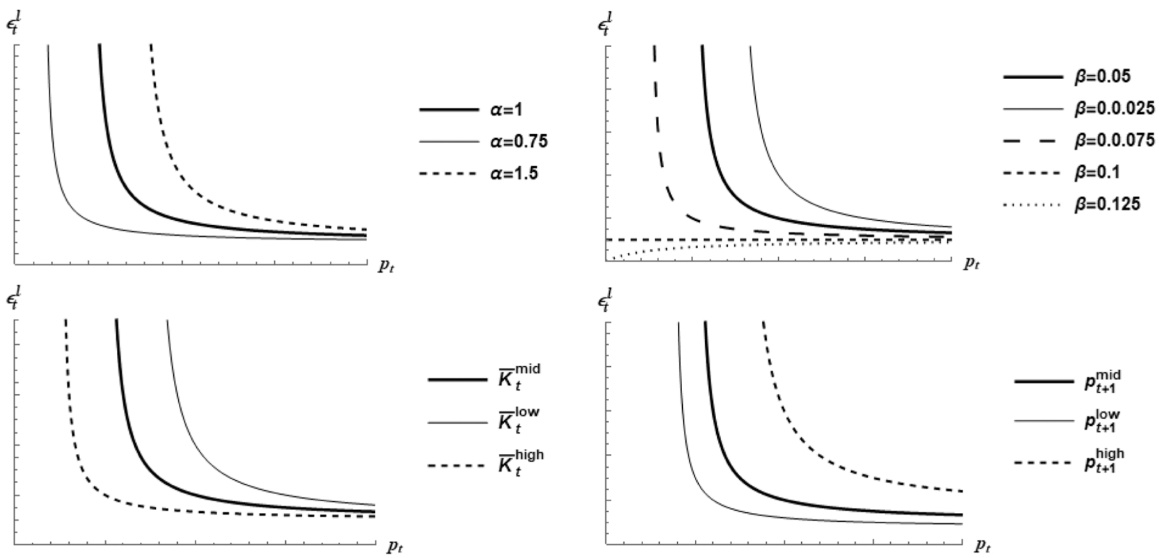

Fig. 9. Shifts in UC price elasticity driven by the key parameters (the thick black line serves as a reference).

We find that a firm's elasticity is adjusted with multipliers carrying the information about changes in the total production level and the role of individual projects in it. The expression for an individual project elasticity is left to Appendix 5; here we consider a multiplier of $\left[1+\frac{\left(Q_t^{UC}-Q_t^{FC}\right)}{\delta_t q_t^l}\right]$ as characterizing the effect of the deficit. This multiplier approaches 1, as FC disappears and $Q_t^{UC} \to Q_t^{FC}$, so that $\epsilon_{t,t}^{FC} \to \epsilon_{t,t}^{UC}$. For $\delta_t > 0$, one can show that the weight is greater than 1, because by definition $\frac{Q_t^{UC}}{Q_t^{FC}} > 1$ and $\frac{\left(Q_t^{UC}-Q_t^{FC}\right)}{\delta_t q_t^l} = \frac{\sum_{l\in L}\eta_{t+1}^l q_t^l}{q_t^l} > 0$. Fig. 10 demonstrates how an individual project's elasticity changes relative to the UC elasticity as the financial deficit value increases. We distinguish projects by their rationing term to show that the elasticity changes the most for the projects that are rationed more than others. In contrast, projects for which the rationing multiplier or the rationing term is close to zero maintain almost the same elasticity.

To understand this somewhat counterintuitive result, we examine the definition of the financial constraint and establish that, keeping all other values the same, financial constraint depends positively on the price level:

$$\delta_t = \sum_{l\in L} k_t^{lUC} - \varepsilon_t \cdot \overline{\Pi}_t = \sum_{l\in L} p_t^l \left(\frac{1}{2\beta\gamma_t^l \widehat{p}_{t+1}^l} - \varepsilon_t q_t^l \overline{K}_t^l\right) + \sum_{l\in L}\left(\frac{\overline{K}_t^l}{2} - \frac{\alpha}{2\beta}\right) \tag{16}$$

A financially constrained firm will be more sensitive to a price change because its investments are affected by the price and also by the budget deficit.

To derive an understanding about CC elasticity, one must account for a change in δ_t associated with PC. The presence of projects for which PC is binding will reduce the financial deficit value relative to the FC case and bring the elasticity value closer to $\epsilon_{t,t}^{UC}$. To summarize:

Corollary 4. *(Price Elasticity):*

The price elasticity of supply is equivalent to the elasticity of a firm's investments in individual 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 it may*

- *increase or decrease with the present net price, depending on the learning parameter's* β *values and expectations about* $\widehat{p}_{t+1}^l$ *,which may prompt the firm to invest "tomorrow";*
- *increase in the presence of deficit* δ_t*, which is positively affected by the price change;*
- *increase if some projects become capacity-constrained, thus reducing the need for rationing.*

4.2. Future price expectations and total price elasticity

Innovations induce producers to bet on new resources, technologies, and applications. Although producers could be fairly certain about the short-term willingness to pay and price, their expectations regarding the future may vary and change over time. The change in expectations alone may lead producers to adjust their investment decisions, for example, to stop investing in diesel vehicles and develop electric cars instead, before today's prices change. To derive the total price elasticity, we include the reaction to expectation changes, first in the unconstrained case and then in the presence of financial deficit. In the latter case, we highlight the difference in UC elasticity.

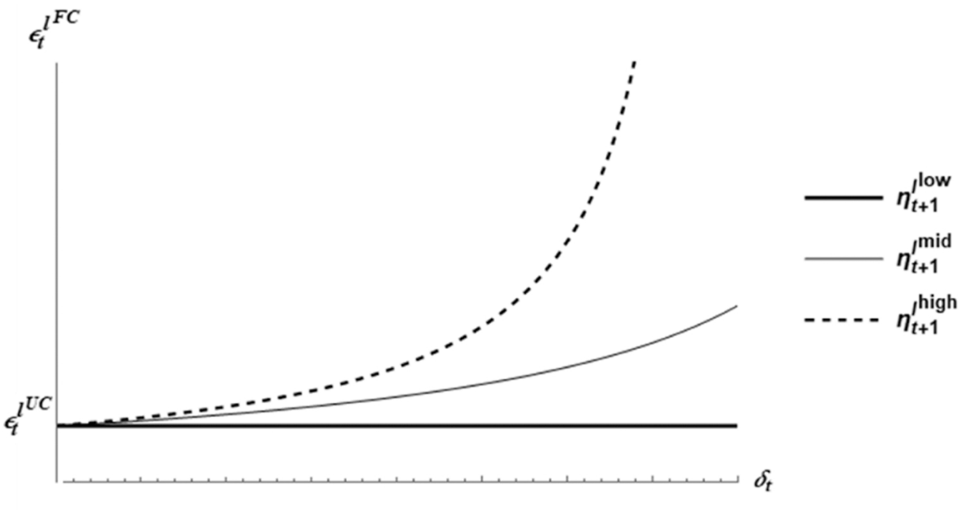

Fig. 10. Changes in individual project elasticity due to financial constraint.

A change in p_{t+1} stems from the fact that in making its investment decisions, the firm takes into consideration the asset value, which is a function of price expectations. Moreover, investments depend positively on today's price, but they are reversely proportional to price expectations, formally: $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} = \frac{-\partial k_t^{l\,UC}}{\partial p_t} \cdot \frac{p_t^l}{\widehat{p}_{t+1}^l}$. Substituting this investment reaction into the total elasticity formula, we obtain:

$$\epsilon_t^{UC} = \sum_l s_t^l \epsilon_{t,t}^{l\ UC} \cdot \left(1 - \frac{\widehat{p}_{t+1}}{p_t} \cdot \frac{p_t^l}{\widehat{p}_{t+1}^l}\right) \tag{17}$$

Although the value considered earlier, $\epsilon_{t,t}^{lUC}$, takes traditionally expected positive values, the second multiplier in Eq. (17) suggests that the price expectations' elasticity and the total elasticity may take negative values. We gain some insight into when it is possible, and we plot $\epsilon_{t,t+1}^{lUC}$ and $\frac{\partial k_t^{lUC}}{\partial p_{t+1}}$ $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}}$ (Fig. 11). In doing so, we reveal how the negative total elasticity emerges owing to the intertemporal price difference: an increase in tomorrow's price incentivizes the firm to invest less today, forgoing the profit in favor of an asset value being evaluated higher at tomorrow's price. The greater the impact of the future price, the more likely the total elasticity is to change its sign.

In addition, the total elasticity of individual projects becomes negative if $\epsilon_{t,t}^{lUC} \to 0$ and $\frac{\partial k_t^{lUC}}{\partial p_{t+1}} < 0$ $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} < 0$, for example, because of high β. Such a case would be hydrogen supply, renewable energy, and, at times, the U.S. production of unconventionals. Companies producing each of those energy resources face an accelerated technological development, concurrent with investments that promote learning and boost productivity. The future price is expected to stay low or decrease with the demand expansion and intensified competition, so $\frac{p_t^l}{p_{t+1}^l} > 1$ and $\epsilon_{t,t}^{lUC} \to 0$.

Mathematically, the total elasticity is negative for projects with $\frac{\widehat{p}_{t+1}}{p_t} > \frac{\widehat{p}_{t+1}^l}{p_t^l}$. Recalling that the difference between the market prices (on the left side of inequality) and the net prices (on the right side of inequality) is the break-even costs, one can infer that the cost stays the same when the elasticity is negative for as long as $\frac{\widehat{p}_{t+1}}{p_t} < 1$ or the price is expected to fall. Otherwise, the multiplier $1 - \frac{\widehat{p}_{t+1}}{p_t} \cdot \frac{p_t^l}{\widehat{p}_{t+1}^l} > 0$. Note that in the provided example as well as throughout the analysis we consider a price-taking firm, whose production is relatively small and does not affect the market price.

If the total price elasticity of supply for individual projects may turn negative, then, depending on the project size, namely their productivity and production capacity determining shares s_t^l, the total firm's supply may be characterized by negative elasticity: $\epsilon_t^{UC} = \sum s_t^l \cdot \epsilon_t^{lUC} < 0$. Similarly, consider an industry having a variety of firms (supporting individual projects), whose price elasticity of supply may be positive or negative depending on their specialization. At times, when the industry is dominated by the firms with $\frac{\widehat{p}_{t+1}}{p_t} > \frac{\widehat{p}_{t+1}^l}{p_t^l}$, its total elasticity of supply may appear to be negative, taking the traditionally expected positive values in other times.

Examining the FC case, we focus on the rationing term, including the rationing multiplier and deficit, both of which are affected by a change in the price expectations, so that:

$$\frac{\partial k_t^{l\,FC}}{\partial p_{t+1}} = \frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} - \eta_{t+1}^l \frac{\partial \delta_t}{\partial p_{t+1}} - \frac{\partial \eta_{t+1}^l}{\partial p_{t+1}} \delta_t \tag{18}$$

Thus, we find that even if $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} > 0$ the price expectations' elasticity of individual projects may be negative if the value of the second summand in Eq. (18) is large enough. By definition $\frac{\partial \eta_{t+1}^l}{\partial p_{t+1}}$ is always negative and approaches zero as p_{t+1} increases, whereas the sign of $\frac{\partial \delta_t}{\partial p_{t+1}}$ $-\sum_l \frac{p_t^l}{\widehat{p}_{t+1}^{l2}}$ depends on the sign of p_t^l. Thus, for startups with negative-return projects, the derivative is positive and the total elasticity sign

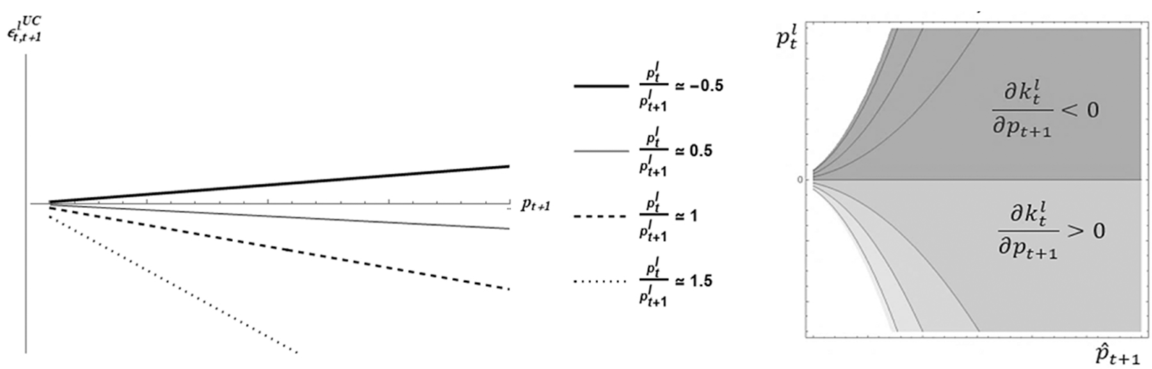

Fig. 11. Elasticity of supply may turn negative owing to the change in future price expectations.

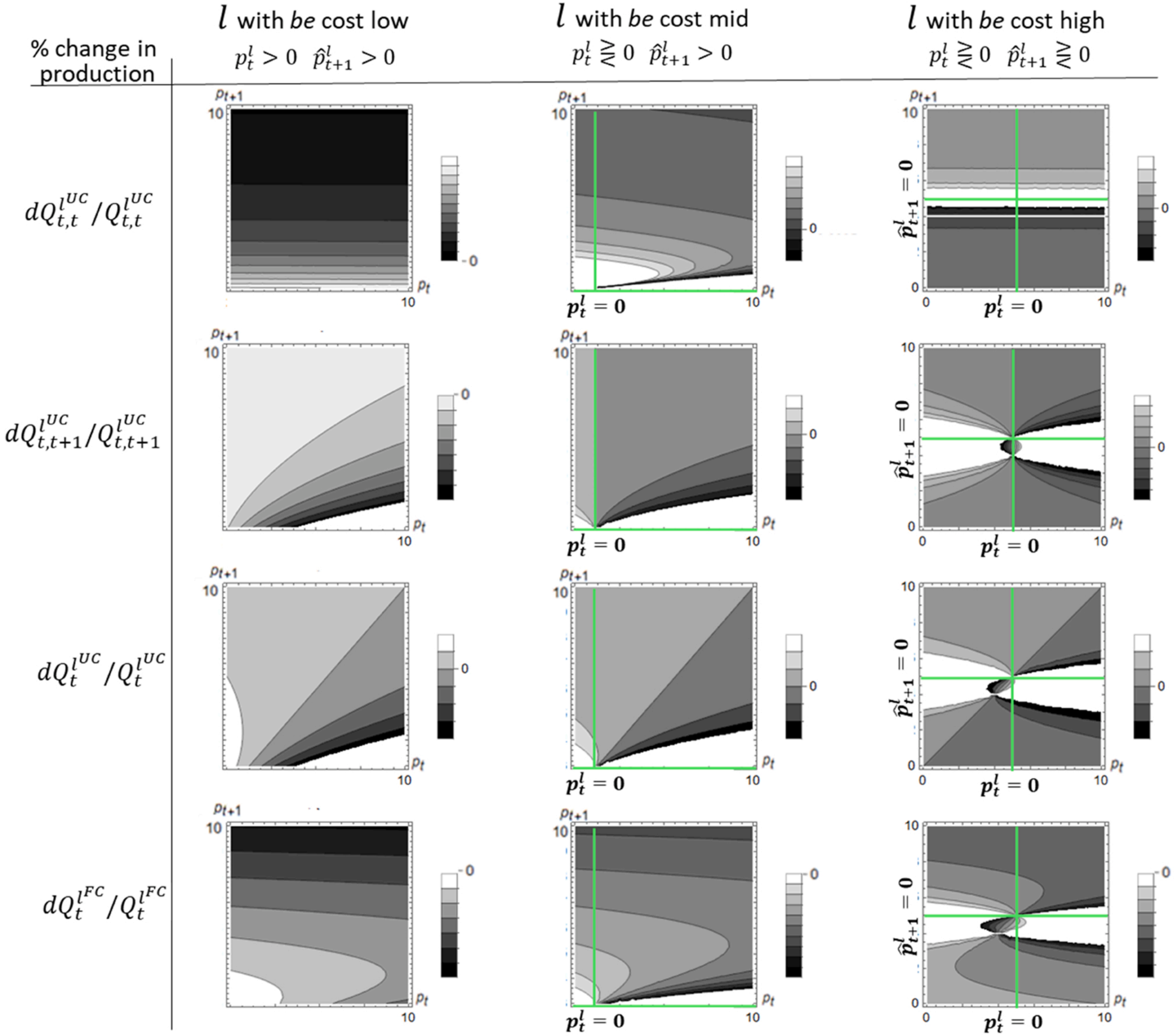

Fig. 12. Supply response to a unit price change under various break-even cost and financial-deficit values.

depends on η^l_{t+1}. For projects with $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}} < 0$, it is sufficient to have both the deficit and the rationing responding positively to guarantee the negativity of $\epsilon^{l\ \ UC}_{t,t+1}$. This may occur if, for instance, an increase in the future net price worsens the situation with the deficit, and, as a result, investments in a given project decrease below the previous level owing to a harsher rationing.

Finally, we arrive at the FC total elasticity expression, revealing the role of the deficit and its rationing:

$$\epsilon^{lFC}_{t,t} + \epsilon^{lFC}_{t,t+1} = \epsilon^{lFC}_{t,t} \cdot \left[\left(1 - \frac{\widehat{p}_{t+1}}{p_t} \cdot \frac{p^l_t}{\widehat{p}^l_{t+1}} \right) - \frac{p_{t+1}}{k_t^{lFC}} \cdot \delta_t \cdot \frac{\partial \eta^l_{t+1}}{\partial p_{t+1}} \right] \tag{19}$$

Analysis of Eq. (19) may be expanded to show how the effect of p_{t+1} can be weaker or stronger owing to PC. With $k_t^{l\,UC} \equiv \overline{K}^l$ some summands in δ_t may turn into constants, resulting in a reduced form of $\frac{\partial \delta_t}{\partial p_{t+1}}$. Then, depending on the sign of the remaining (not affected by PC) $\frac{\partial k_t^{l\,UC}}{\partial p_{t+1}}$ derivatives, the price expectations' elasticity may either increase or decrease. Thus, the firm may appear to be less reactive or sensitive to a price change, unable to increase its investments beyond PC. To untangle the complexity of the total elasticity behavior further and to develop insight into the derived formulas, we turn to simulations and graphical illustrations.

4.3. Illustrative simulations

With U.S. shale gas production in mind, we assign productivity improvements parameters based on the estimates from the Marcellus play, averaged from 2010 through 2019, namely $\alpha = 1.05$ and $\beta = 0.06$ calculate the point elasticity components, the price elasticity, the expectations elasticity, and the total elasticity with and without FC. We present contour plots with shading, showing how production may change in $(p^l_t; \widehat{p}^l_{t+1})$ coordinates for the three cases with respect to the break-even (*be*) costs to include the projects with negative as well as positive net prices (Fig. 12).

The four rows of plots in Fig. 12 depict differences in the elasticities of projects yielding negative and positive returns, whose values may or may not improve in the future. The term $\widehat{p}^l_{t+1}$ stays in the denominator of the optimal investment formula, and therefore, some plots have discontinuity. In the first two rows, we exhibit the changes separately in the supply to a unit change in the current (first-row) versus future (second-row) prices. 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 a plot illustrating the effect of a non-zero financial deficit. We perform the calculations assuming that productivity improvements parameters are the same across all projects, and we set the uncertainty parameter equal to 1.

In the case of a zero financial deficit, the contour plots in the third row show how the $\frac{p_t}{p_{t+1}} = 1$ line divides the plot into areas with a positive and negative supply change associated with a unit price increase. In other words, we 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. It is interesting that the line determining the elasticity sign switch remains the same, but the shape of the contours changes with the project profitability, as demonstrated by the shading patterns. Looking at the first- and second-row plots, one can notice that the evolution of contours is determined by the break-even cost value and the symmetry lines $p^l_t = 0$ and $p^l_{t+1} = 0$.

Plots in the fourth row reflect the nontrivial nature of the supply response. The first two columns of plots have a price axis that crosses at values above the break-even cost and shows only the positive net price regions, without the discontinuity shown in the last column of plots. As a result, it is only on the bottom right plot that one can see that the zero net price value sets a gravity center for the contour propagation. Under financial deficits, the properties of the sign-changing line are inherited by the nonlinear contour, and the response can take positive and negative values both above and below the $p_t = p_{t+1}$ line.

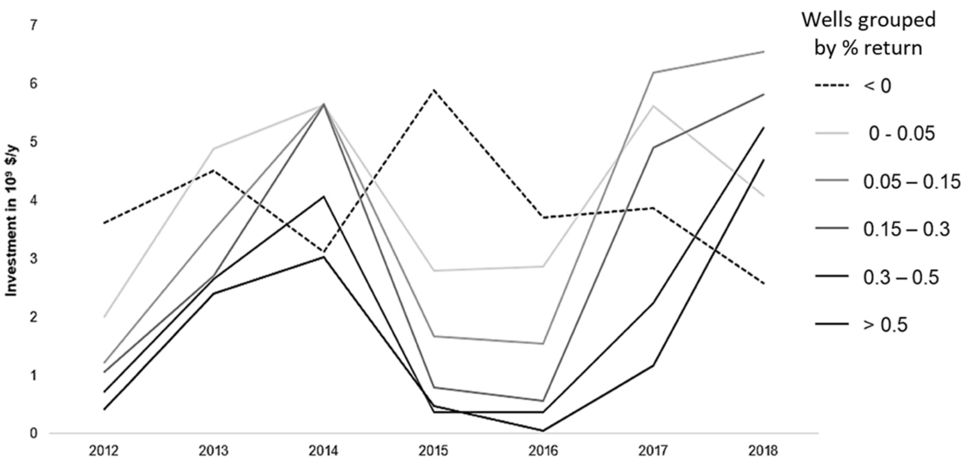

Fig. 13. Investment dynamics of Marcellus play wells with positive and negative returns.

We picked the break-even cost and other values, including price levels, to reflect the situation around the Marcellus play to be able to verify our theoretical findings. We leave a thorough empirical investigation for future work, relying here on the data and analysis presented by Ikonnikova et al. (2018). We turn to the Marcellus well statistics, with wells grouped by their profitability or return. Following the discussion in the original report, we remove almost 10% of wells, which are estimated to recover less than 50% of their capital costs in 10 years. We assume that low-profit values may be associated with erroneous or missing production data and account only for wells that allow for positive profit and/or asset value. The remaining wells are split into tiers, with the negative-return projects being depicted by the dashed line (Fig. 13). The plot of investment dynamics across different groups shows a close correlation to the natural gas price for all except the negative-return, or *à la* R&D projects.

Viewing the Marcellus play as a bundle of investment (well) projects, we can discuss results from our model in the context of Marcellus investments and the elasticity of the play supply. We turn to Fig. 13 and apply information found on improvements in production efficiency and future price forecasts. Using the base-case price projections reported by the U.S. Energy Information Administration (EIA, 2014, 2016, 2017), we estimate the near-term and future prices, and differences in relative change over time, keeping constant the break-even cost parameter for simplicity. Applying the unconstrained solution, we calculate:

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

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

$$k_{2015}^{0.5-085\,UC} \quad \Big|_{p_t=1.71} \approx -\frac{1.3}{2\cdot 0.10\cdot 1.2} - \frac{1.0}{2\cdot 0.10} + \frac{\overline{K}_t^l}{2} = -5.5 + \frac{\overline{K}_{2015}^l}{2}$$

Assuming that the change in the production potential is small, we find that despite increasing p_t the remaining fairly constant p_{t+1} value results in the decreasing first summand, so the investments would increase and the elasticity would be negative. Had the investment potential grown thanks to the improved ability to extract resources from locations previously viewed as undevelopable, the negative elasticity values would be even greater. The inclusion of the deficit term with the rationing multiplier may further explain the increase in 2015 investments, but detailed empirical analysis is beyond the scope of this paper. 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.

Hence, addressing the second major research question asked, we have managed to reveal conditions for the negative elasticity theoretically, and we demonstrate the findings through simulations and with data-driven examples. Proceeding to our conclusions, we summarize our findings and relate them to a discussion of the implications and venues that other researchers can address in further analysis.

5. Conclusions, implications, and venues for future research

We initiated our analysis being puzzled by the evidence of substantial investments in negative-return projects and the repeatedly reported negative elasticity of supply phenomena. In some previous studies, these phenomena were attributed to an estimation error or were neglected as a short-term event (Gomes, 2001). With insights gained from analyzing the unconventional oil and gas supply in the United States, we developed a model that captures the trade-off between investing in value extraction and value expansion. Producers may run out of investment options unless they invest in novel projects, expanding future production capabilities. For instance, a firm may risk going out of business unless they invest in carbon-offset projects or alternative technologies. Automotive firms having only oil-product fueled vehicles risk losing their market share unless they invest in hybrid, electric, and hydrogen technologies.

Viewing negative-return projects as a necessary condition for gaining experience and learning, we ask what influences would boost production efficiency and market potential in the future. Our model explains the balance between profitable and unprofitable projects, contributing to the discussion on the transition from fossil to renewable energy (Brockway, Owen, Brand-Correa, & Hardt, 2019). Examining potential driven incentives for supply, we build a bridge between exhaustible-resources literature and R&D models. To accommodate the diversity of views on investments, we strengthen that bridge by allowing for financial deficits, a topic that has received little attention in both strands of literature. The introduction of financial deficits helps us reveal what else may force producers to expand or shrink their investments in novel projects, and to bring together intertemporal and across-project opportunity-cost drivers.

Our derived understanding seems to be especially useful for an energy transition analysis focused on the transformation of energy-asset portfolios, transition financing issues, and energy supply sustainability. The energy industry has been reporting a decreasing average return on investment: the major energy company Exxon has fallen out of the top 10 companies of the S&P 500. Despite the continuous growth in fossil-energy consumption, energy prices have undergone extreme volatility, having both unforeseen fluctuations and expected adjustments. In this context, the major industry players, including BP, Equinor (formerly Statoil), and 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, these companies have often been criticized for taking a high risk. Our model gives insight into what may justify these decisions, even under high uncertainty.

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 nonintuitive effect on the total (e.g., energy) supply. For example, this result is crucial for understanding why and how the introduction of electric vehicles may affect the elasticity of supply in the automotive industry or how the pandemic-related worsening financial performance in 2019–2022 may reduce some firms' ability to invest and respond to price changes, thereby reducing their elasticity of supply. However complex, our model may become a useful tool for policy and regulatory analysis, helping analysts to estimate, among other questions, the effect of changes in future price or cost regulations and financial support.

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

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

A different line of research that may continue our analysis relates to 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 their small counterparts. On the other hand, startups focused on the investment and production potential, or value of the growth assets, are extremely innovative compared to larger firms, which must generate profit and follow a stricter financial discipline.

To conclude, we see a variety of applications, extensions, and enhancements for the presented model, such as theoretical, applied, and empirical. Stemming from energy-industry observations, our model is equally usable in other industries with the correct specification and parameter assessments. Our study will interest industrial and financial economists, and it also provides food for thought for policymakers and regulators because it helps explain and accommodate numerous previous theories regarding investments and supply. Understanding the supply consequences of investment decisions is critical for firms' resiliency, and it is also critical for policymakers and regulators as they develop effective incentives for the energy transition (Beviá et al., 2020; IEA, 2020, 2019a, 2019b; IHS Markit, 2019; Ilyina & Samaniego, 2012). Untangling the trade-offs faced by a real-world firm, associated with investments in alternative energy and innovative projects, our results will be especially useful for environmental, social, and governance (ESG) evaluations and strategies (Armstrong & Huck, 2010; Grim & Berkowitz, 2020; Sundaram & Inkpen, 2004).

Acknowledgements

We acknowledge the support of the Tight Oil Resource Assessment consortium at the Bureau of Economic Geology. We are also grateful to IHS for access to their databases. Emery Goodman and Qian Yang, our colleagues at the Bureau, provided exceptional feedback to improve this manuscript. Any errors are our own.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jeconbus.2022.106067.

References

Abel, A., Dixit, A., Eberly, J., & Pindyck, R. (1996). Options, the value of capital, and investment. *The Quarterly Journal of Economics, 111*(3), 753–777.

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. MPRA Paper, University Library of Munich, Germany, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1553645.

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.

Baik Y., Hensley R., Hertzke P. & Knupfer S. , (2019). Making electric vehicles profitable. McKinsey & Company article, March 8, 2019 (assessed 12 January, 2022). https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable.

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.

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

Bolton, P., Wang, N., & Yang, J. (2019). Investment under uncertainty and the value of real and financial flexibility. *Journal of Economic Theory, 184*, 1–58.

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.

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 Gaseta Journal, 111*(9), 88–95.

Caballero, R. J., & Pindyck, R. S. (1996). Uncertainty, investment, and industry evolution. *International Economic Review, 37*(3), 641–662.

Campiglio, E., Kemp-Benedict, E., Godlin, A., & Matikainen, S. (2017). The tightening links between financial systems and the low-carbon transition. In P. Arestis, & M. Sawyer (Eds.), *Economic policies since the global financial crisis*. Springer.

Campiglio E., Monnin P., & von Jagow A. , (2019). Climate risks in financial assets. Council on Economic Policies, Discussion Note. https://www.cepweb.org/wp-content/uploads/2019/11/CEP-DN-Climate-Risks-in-Financial-Assets.pdf.

CDP (formerly the Carbon Disclosure Project), (2019). Major risk or rosy opportunity: are companies ready for climate change? https://www.cdp.net/en/research/global-reports/global-climate-change-report-2018/climate-report-risks-and-opportunities (accessed 18 October 2021).

Chakravorty, U., Magne, B., & Moreaux, M. (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.

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, 45*(7), 3883–3898.

Dahl, C., & Duggan, T. E. (1996). U.S. energy product supply elasticities: a survey and application to the U.S. oil market. *Resource and Energy Economics, 18*(3), 243–263.

David, J. D., & Sibilkov, V. (2010). Financial constraints, investment, and the value of cash holdings. *Review of Financial Studies, 23*(1), 247–269.

Davis, G. A., & Owens, B. (2003). Optimizing the level of renewable electric R&D expenditures using real options analysis. *Energy Policy, 31*(15), 1589–1608.

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). https://www.greentechmedia.com/articles/read/the-reality-behind-green-hydrogens-soaring-hype (accessed 18 October 2021).

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty* (p. 468). Princeton University Press.

EIA, (2014). Some Appalachian natural gas spot prices are well below the Henry Hub national benchmark. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=18391.

EIA, (2016). Trends in U.S. oil and natural gas upstream costs. Energy Information Administration. https://www.eia.gov/analysis/studies/drilling/ (accessed 18 October 2021).

EIA, (2017). Natural gas pipeline projects lead to smaller price discounts in Appalachian region. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=32512.

Fisher, W. L., Angino, E. E., Claypool, G. B., Henshaw, P. C., Knapp, R. M., Leighton, M. W., … Vail, P. R. (1988). *Scientific drilling and hydrocarbon resources* (p. 89). The National Academies Press (The National Academies of Sciences).

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

Gaudet, G., Moreaux, M., & Salant, S. W. (2001). Intertemporal depletion of resource sites by spatially distributed users. *American Economic Review, 91*(4), 1149–1159.

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

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.

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.

Gülen, G., Ikonnikova, S., Browning, J., & Tinker, S. W. (2014). Fayetteville shale production outlook. *SPE Economics & Management, 7*, 2.

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

Hausman C. & Kellogg R. , (2015). Welfare and distributional implications of shale gas. Brookings Papers on Economic Activity. https://www.brookings.edu/bpea-articles/welfare-and-distributional-implications-of-shale-gas/.

He, H., & Pindyck, R. S. (1992). Investments in flexible production capacity. *Journal of Economic Dynamics and Control, 16*(3–4), 575–599.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy, 39*(2), 137–175.

Howard J.L. & Liang S. (2018). US timber production, trade, consumption, and price statistics, 1965–2017. The economics of exhaustible resources. Res. Pap. FPL-RP-701. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. 96 p., 701, pp. 1–96.

IEA, (2019b). World Energy Outlook 2019. International Energy Agency. www.iea.org/weo2019.

IEA, (2019a). The Oil and Gas Industry in Energy Transitions—World Energy Outlook. International Energy Agency Special Report. https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions.

IEA, (2020). World Energy Investment 2020. International Energy Agency. https://www.iea.org/reports/world-energy-investment-2020.

IHS Markit, (2019). Oil and gas company climate indicators highlight consensus on risks, divergence in response, climate and carbon insight. https://ihsmarkit.com/research-analysis/energy-transition-why-now-is-the-time-for-a-new-narrative.html.

Ikonnikova, S., Smye, K., Browning, J., Dommisse, R., Gülen, G., Hamlin, S. … Vankov, E. , (2018). Final Report on Update and Enhancement of Shale Gas Outlooks. U.S. Department of Energy, Office of Scientific and Technical Information, doi:10.2172/1479289.

Ikonnikova, S. A., Male, F., Scanlon, B. R., Reedy, R. C., & McDaid, G. (2017). Projecting the water footprint associated with shale resource production: Eagle ford shale case study. *Environmental Science and Technology, 51*(24), 14453–14461.

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

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.

Kellogg, R. (2011). Learning by drilling: Interfirm learning and relationship persistence in the Texas oil patch. *The Quarterly Journal of Economics, 126*(4), 1961–2004.

Krichene, N. (2002). World crude oil and natural gas: a demand and supply model. *Energy Economics, 24*(6), 557–576.

Levine, O., & Warusawitharana, M. (2021). Finance and productivity growth: firm-level evidence. *Journal of Monetary Economics, 117*, 91–107.

MacKay, P. (2003). Real flexibility and financial structure: An empirical analysis. *The Review of Financial Studies, 16*(4), 1131–1165.

Majd, S., & Pindyck, R. S. (1987). Time to build, option value, and investment decisions. *Journal of Financial Economics, 18*(1), 7–27.

Mason, C. F. (2001). Non renewable resources with switching costs. *Journal of Environmental Economics and Management, 42*, 65–81.

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.

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.

Medlock, K. B., III (2012). Modeling the implications of expanded US shale gas production. *Energy Strategy Reviews, 1*(1), 33–41.

Mello, A. S., & Parsons, J. E. (1992). Measuring the agency cost of debt. *TheJournal of Finance, 47*(5), 1887–1904.

Miao, J. (2005). Optimal capital structure and industry dynamics. *The Journal of Finance, 60*(6), 2621–2659.

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.

Modigliani, F., & Miller, M. H. (1958). The cost of capital, corporation finance and the theory of investment. *American Economic Review, 48*(3), 261–297.

Newell, R. G., Prest, B. C., & Vissing, A. B. (2019). Trophy hunting versus manufacturing: the price responsiveness of shale gas. *Journal of the Association of Environmental and Resource Economists, 6*(2), 391–431.

Obersteiner, M., Azar, C., Möllersten, K., Riahi, K., Moreira, J. R., Nilsson, S., & Yan, J. (2002). Biomass energy, carbon removal and permanent sequestration – a "real option" for managing climate risk. IIASA Interim Report. http://pure.iiasa.ac.at/id/eprint/6743/.

Paddock, J. L., Siegel, D. R., & Smith, J. L. (1988). Option valuation of claims on real assets: The case of offshore petroleum leases. *The Quarterly Journal of Economics, 103*(3), 479–508.

Pammolli, F., Magazzini, L., & Riccaboni, M. (2011). The productivity crisis in pharmaceutical R&D. *Nature Reviews Drug Discovery, 10*(6), 428–438.

Ponce M. & Neumann A. , (2014). Elasticities of supply for the US natural gas market. DIW Berlin Discussion Paper, No. 1372. German Institute for Economic Research. https://www.diw.de/documents/publikationen/73/diw_01.c.441773.de/dp1372.pdf.

Pindyck, Robert S. (2004). Volatility and commodity price dynamics. *The Journal of Futures Markets, 24*(11), 1029–1047. https://doi.org/10.1002/fut.20120

Reinartz, S. J., & Schmid, T. (2016). Production flexibility, product markets, and capital structure decisions. *The Review of Financial Studies, 29*(6), 1501–1548.
Reuter, W. H., Fuss, S., Szolgayová, J., & Obersteiner, M. (2012). Investment in wind power and pumped storage in a real options model. *Renewable and Sustainable Energy Reviews, 16*(4), 2242–2248.
Ross, S. A., Westerfield, R. W., & Jordan, B. D. (1993). *Fundamentals of corporate finance* (second ed.). Homewood, IL: Irwin Press.
Smith, J. E., & Nau, R. F. (1995). Valuing risky projects: Option pricing theory and decision analysis. *Management Science, 41*(5), 795–816.
Smith, J. L., & Lee, T. K. (2017). The price elasticity of U.S. shale oil reserves. *Energy Economics, 67*(C), 121–135.
Sundaram, A. K., & Inkpen, A. C. (2004). The corporate objective revisited. *Organization Science, 15*(3), 350–363.
Thompson, M., Davison, M., & Rasmussen, H. (2009). Natural gas storage valuation and optimization: A real options application. *Naval Research Logistics, 56*(3), 226–238.
Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Economics, 31*(5), 648–666.
WEC, (2019). World Energy Issues Monitor 2019 | Managing the Grand Energy Transition. World Energy Council. 1.-World-Energy-Issues-Monitor-2019-Interactive-Full-Report.pdf (worldenergy.org).
Wei, Z. (2015). Financial constraint, government R&D subsidies and corporate R&D investment: an empirical study of China's strategic emerging industries. *Contemporary Finance & Economics, 11*, 86–97.