Coupled Investments in SMRs and Industrial Sites: a Real Options Analysis

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Abstract

As meeting net-zero targets grows imperious, decarbonising industrial heat has become a pivotal challenge for policymakers and industrial stakeholders alike. However, investment in low-carbon heat technologies is still timid. This is hindered by risk aversion, the irreversibility of investment, and the fragmented nature of industrial heat demand, among other factors.

This paper explores the potential role of Small Modular Reactors (SMRs) in supplying decarbonised heat and electricity to industrial sites. These technologies offer high-temperature capabilities of decarbonized heat production at stable cost, yet face significant economic and infrastructural barriers. In the context of a possible deployment of such technology to suply heat and/or electricity to an industrial firm, emerges the issue of agreements on bilateral contracts between SMR developers and industrial firms, which may offer a viable pathway to overcome investment hurdles and align supply with demand.

To investigate this, we develop a coupled investment model within a Real Options Analysis framework, capturing the strategic decision-making processes for both an industrial firm and a SMR developer. The model considers five investment or contracting options for the industrial firm and three for the SMR firm, incorporating the irreversibility of capital expenditures, risk aversion from both agents, and the potential for bilateral contracting in heat and electricity supply.

Our results indicate that, under our numerical assumptions, the probability of an agreement between the industrial firm and the SMR firm on a bilateral contract for heat supply in 2040 drops from 70% to around 10% when irreversibility is accounted for, and from 75% to 20% in 2050. Sensitivity analyses are led to quantify the effet of SMR investment costs, and commoditiy prices initial values and volatilities.

Disclaimer

1 Introduction

As governments and industries commit to net-zero targets, the decarbonisation of industrial process heat emerges as a critical challenge, especially in decarbonising energy intensive industries (Nurdiawati & Urban, 2021). In the EU, industrial heat—used in processes such as drying, melting, and chemical reactions—accounts for about two-third the industrial energy demand, and three-quarters of the greenhouse gas emissions from the industrial sector (since it is predominantly supplied by fossil fuel combustion) (EEA, 2024). Transitioning to low-carbon heat sources is therefore essential, but it entails significant capital investment, long planning horizons, and systemic changes to existing infrastructure (Thiel & Stark, 2021).

However, investment in industrial process heat decarbonisation remains constrained by several factors. One of them is risk aversion from industrial firms, particularly in relation to the irreversibility of investment decisions (Nishimura & Ozaki, 2007; Westner & Madlener, 2012). Once a firm commits to a specific heat supply configuration—whether it involves upgrading existing boilers, switching fuels, or connecting to an external heat network—it effectively locks in a technological and economic pathway for decades. Reversing such decisions is technically difficult and costly, especially when they involve long-lived infrastructure or contractual obligations. As a result, firms may delay or avoid investments altogether, waiting for greater certainty in energy prices, regulatory frameworks, or market signals (Deng & Hao, 2024)

In the context of the development of innovative, decarbonised heat production technologies, Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) are gaining attention as potential solutions for providing low-carbon, medium-to-high temperature heat to industrial sites. SMRs and AMRs offer several advantages, including modularity, scalability, and a smaller physical footprint compared to conventional nuclear reactors (IAEA, 2017). Moreover, technologies such as High-Temperature Gas Reactors, Molten Salt Fast Reactors, and Liquid-Metal Fast Reactors can reach temperatures above 400°C (Peakman & Merk, 2019)—levels that are higher than for Pressurized Water Reactors, which remain the most widely developed nuclear technology globally. For these advanced reactor technologies, the production in cogeneration mode of decarbonised heat and electricity represents a key value proposition for their integration into future energy systems (Carlsson et al., 2012). However, their deployment requires large investments. Their integration into industrial ecosystems depends not only on technological readiness but also on the development of new business models and regulatory support mechanisms that can de-risk investment (Mignacca et al., 2020).

Currently, most industrial sites rely on on-site heat generation, typically using natural gas or coal-fired boilers (Thiel & Stark, 2021). This model offers operational control and flexibility but is increasingly incompatible with decarbonisation goals. A shift toward external heat supply models, such as district heating networks or direct heat supply from SMRs, could represent a transformative approach to integrate decarbonized heat sources into the industrial heat supply mix. However, their success hinges on aligning industrial heat demand with the development of low-carbon supply infrastructure, and on creating investment conditions that mitigate risk and encourage long-term commitment (Peakman & Merk, 2019). The emergence of bilateral contracts between exterior-to-site decarbonised heat producers and industrial firms is therefore a topic of interest in studying the modalities of industrial process heat decarbonisation.

This paper aims to build on existing literature regarding investments in decarbonising industrial processes, by quantifying the economic interest of SMRs compared to conventional technologies. The research question we are adressing is the following:

"*Under which circumstances would an industrial firm and a SMR firm agree on a contract for heat or heat-and-electricity supply, instead of the industrial firm investing in and operating its own on-site heat production unit?*"

More specifically, it will focus on three main aspects in studying the joint decision-making process from the perspective of industrial and SMR firms. Firstly, the irreversibility of these investments in terms of capital expenditure recovery will be considered. Secondly, it will consider the possibility of investing in an SMR, with the option for bilateral contracting between the SMR firm and the industrial firm for commodity supply, in competition with conventional solutions. Thirdly, these commodities will include both heat and electricity, which will be priced using a stochastic behavior assumption.

We develop a coupled investment model in a Real Options Analysis framework for both the industrial firm and the SMR firm. The industrial firm is assumed to consume heat and electricity. At initial stage, the industrial firm is assumed to possess an on-site heat generation unit to cover its full heat demand, and to source its electricity consumption from the grid. From there, it has the choice between five options: investing in an on-site heat-only generation unit, investing in an on-site cogeneration unit, signing a bilateral contract with the SMR firm for heat (only) supply, signing a bilateral contract with the SMR firm for heat and electricity supply, or waiting. On the other side, the SMR firm is faced with a three-options choice: investing and signing a bilateral contract with the industrial firm for heat supply, investing and signing a bilateral contract with the industrial firm for heat and electricity supply, or waiting.

The rest of the paper is organized as follows. Section 2 gives background on the literature related to Real Options Analyses, and investment decision-making in industrial heat equipments. Section 3 presents our mathematical model, with a step-by-step approach to upgrade from a simple to a two-agent Real Options framework. Then, Sections 4 and 5 provide a numerical application to a real-world case. We finally discuss the policy implications and conclude the paper in Section 6.

2 Background

2.1 Industrial heat decarbonization

The seminal work by Joskow and Jones, 1983 laid the groundwork for understanding the economics of industrial cogeneration. Their analysis highlighted cogeneration as a method to improve energy efficiency by simultaneously producing electricity and process steam, thereby reducing reliance on separate generation systems. They emphasized that while cogeneration offers thermodynamic advantages, its economic viability depends heavily on fuel and electricity prices, plant-specific technical characteristics, and policy incentives. A growing body of literature has since explored pathways to decarbonize industrial heat, particularly in energy-intensive sectors. Dumont et al., 2023 investigate the potential use of high-temperature heat pumps (HTHPs) in the German food and beverage industry from a technoeconomic perspective. Their results suggest that HTHPs could meet 12 TWh of heat demand and reduce emissions of the sector by 9%. They show that a carbon tax of €38/tCO_2 or higher, HTHPs become cost-competitive against fossil-based alternatives. Mallapragada et al., 2023 focus on the decarbonization means of the chemical industry, identifying ethylene and ammonia as major GHG contributors. They evaluate four electrification pathways for heat production in this sector: direct electrification, the use of hydrogen, electro-chemical technologies and plasma-based technologies. The study emphasise the importance of grid integration and flexible operations for cost-effective decarbonisation, as well as highlighting the key uncertainties affecting the different pathways in terms of cost and technological readiness. Madeddu et al., 2020 conduct a bottom-up analysis of 11 industrial sectors in Europe, finding that 78% of energy demand covered by their analysis is electrifiable with existing technologies, and up to 99% with emerging ones. They emphasize the importance of combining industrial process heat electrification with industrial sites demand flexibility, and economic incentives to investments through GHG taxation and/or low-carbon technologies support schemes, contingent on a decarbonized power sector. Taking a holistic approach to support industries in identifying and prioritising cost-effective decarbonisation pathways, Maghrabi et al., 2023 propose a comprehensive framework focused on targeted energy efficiency measures. Acknowledging the diversity of industrial processes, they outline a structured methodology beginning with top-down peer benchmarking to detect performance gaps across products, plants, and equipment. The framework then guides decision-makers through equipment gap analysis, process design optimisation, and recovery of residual waste heat. A key emphasis in their conclusions is placed on the implementation of operational energy management programs to sustain and enhance energy performance over time. Finally, Nurdiawati and Urban, 2021 provide a comprehensive review of decarbonization strategies for energy-intensive industries such as steel, cement, and pulp and paper. They highlight electrification, fuel switching, and CCS as key technologies, and present Sweden as a case study for successful policy-driven industrial transformation. They emphasize that financial support on low-carbon technologies, GHG taxation, and R&D efforts in emerging technologies are all needed to successfully decarbonize energy-intensive industries.

With a zoom on Small Modular Reactors, which are increasingly viewed as a promising solution for industrial heat decarbonisation due to their scalability, passive safety, and potential for co-generation, different studies have examined their interest in providing low-carbon heat to industrial processes. Carlsson et al., 2012 explore the suitability of small nuclear reactors for heat process supply in European industries. They highlight the potential of combined heat and power (CHP) reactors to support EU decarbonisation goals while ensuring production and cost stability. High-temperature reactors (200–550°C) are identified as ideal for producing high-value heat. They find the greatest market potential in chemical/petroleum, paper, metal, and bioenergy sectors with capacities of 50–250 MW_{th}. Finally, they identify levelized cost targets for nuclear to compete with coal and gas CHP. Sensitivity analysis reveals capital costs of new reactors as the key competitiveness driver. Then, Peakman and Merk, 2019 assess current and future UK industrial requirements for high-temperature heat and evaluate how various reactor types could meet these needs. While reactors like High Temperature Gas Reactors, Very High Temperature Reactors, or Molten Salt Reactors offer higher temperature capabilities, the study finds that most industrial heat demand can be served by a Light Water Reactors and Liquid Metal Fast Reactors. They detail for the different industrial sectors (Chemicals, Food and Beverage, Pulp and paper, Metals,etc.) the suitability of the different reactors technologies. Finally, Vanatta et al., 2023 conducted a technoeconomic analysis of SMRs for industrial process heat across 357 U.S. facilities. They found that SMRs are not viable for heat-only applications at current gas prices but become competitive when also participating in electricity markets. Their model identified up to 33.9 GW_{th} of SMRs as economically viable, potentially avoiding 4 million tons of CO_2 emissions annually.

2.2 Real options

The real options framework

The decarbonisation of industrial heat involves complex investment decisions under uncertainty, often characterized by irreversibility and long planning horizons. When this irreversibility is accounted for in an agent's decision-making process, the option to defer an investment decision has a value in itself due to the additional information gained from waiting. The foundational framework of Real Options Analysis (ROA), as developed in (Dixit & Pindyck, 1994), provides a robust method for evaluating such decisions by accounting for this value of flexibility and the strategic timing of investments. Three approaches to solving real options problems are generally distinguished: the closed-form (using Black-Scholes equations) approach (Brown & Davis, 1998; Dixit & Pindyck, 1994; McDonald & Siegel, 1986), the binomial lattice approach (Copeland, 2001; Cox et al., 1979) and the Monte-Carlo approach (Glasserman & Yu, 2004; Longstaff & Schwartz, 2001). In the context of energy planning and the low-carbon transition of energy systems, real options methods have been employed in a variety of economic assessments of low-carbon technologies, including PV (Zhang et al., 2016), CCS retrofitting of gas plants (Agaton, 2021; Al-Obaidli et al., 2023), Small Modular Reactors (Najafi & Talebi, 2021), or wind power (Madlener et al., 2019). [1]

Real options in the energy sector

In the field of industrial commodity generation, Wickart and Madlener, 2007 use the closed-form approach to model the choice between cogeneration and heat-only systems for industrial firms, incorporating energy price volatility and CO_2 taxation to determine optimal investment timing and technology selection. They extend the ROA framework to model the decision-making process in a two-commodity setting, when an industrial firm has a choice to make between a separate and a coupled production technology. In the context of decentralized energy systems, A. S. Siddiqui and Maribu, 2009 analyze microgrid investment strategies under natural gas price uncertainty. They build a sequential RO model for investment in heat and power on-site units, using the closed-form approach. They show that higher volatility favors sequential investment in distributed generation and heat exchangers. Zooming out of the industrial decarbonization sector, the closed-form approach of real options solving has also been extended to account for cases involving several mutually exclusive options available to the decision-maker (Cret et al., 2024; A. Siddiqui & Fleten, 2010) , to model two competing or collaborating firms (Banerjee et al., 2014; Paxson & Pinto, 2005) , and to extend to cases with two or more stochastic variables (Armada et al., 2013; Rohlfs & Madlener, 2011; Schmit et al., 2011).

To overcome the limitations of analytical real options solutions, numerical implementations through dyamic programming methods has been also developed to solve real options problem. In the field of

[1] See Nadarajah and Secomandi, 2023 for a review of operations literature applying real options to the energy sector.

industrial decarbonisation, Tautorat et al., 2025 introduce a real options valuation model to assess industrial heat decarbonization under uncertainty, focusing on process heat in the Swiss chemical sector. Their findings show that investment choices vary by temperature range, with low-temperature plants favoring electrification and high-temperature ones leaning toward biomass and CCS. Their paper emphasize that policy and market uncertainties significantly influence investment timing. Leveraging on the capabilities of multi-dimensional lattices, Rohlfs and Madlener, 2014 present a multivariate binomial tree real options model to evaluate power generation technologies under uncertainty, incorporating technology-specific risks and CO_2 policy scenarios. Their results show that investment timing and technology preference—especially for CCS—are highly sensitive to carbon pricing mechanisms, with stronger incentives to invest under price floors and carbon taxes than under stochastic ETS pricing.

Least Square Monte Carlo to solve real options problems

In the case of continuous state variables, there is an infinite number of states possible to the exogenous underlyings. Cret et al., 2024 have developed a Monte Carlo simulation-based real options model, solved using dynamic programming, to assess the effectiveness of greenhouse gas (GHG) emission intensity standards in promoting technological change in the container ship industry amid uncertainty over fuel prices, with a modelling horizon spanning three timesteps of one year each. However, using dynamic programming to solve the decision-making process at each node of the Monte Carlo network is intractable in practice as soon as the number of timesteps and options increases due to the curse of dimensionality[2]. To treat with this rational, one can make use of the framework developed by Longstaff and Schwartz, 2001 to value American options. Their approach, called the Least-Square Monte-Carlo (LSM) algorithm, is described with more details in section 3. Drawing on this foundational paper, the work of Nadarajah et al., 2017 compare two variants of the LSM algorithm to value operation options in an energy storage setting. In the field of power grid investment, Pringles et al., 2015 use the LSM method to value the option to defer power transmission investments. They show how factors like option maturity, capital costs, and initial outlay influence investment timing and identifying optimal conditions for executing, postponing, or rejecting projects. In their example case, they show that the acquisition of

[2] On this matter, see the details provided in (Nadarajah et al., 2017).

a licence for a power interconnection project construction – which is deemed unprofitable under traditional evaluation methods (NPV maximisation) – becomes economically viable when the option to defer investment is considered. By acquiring a building permit and waiting for key uncertainties to resolve before actually starting the construction, investors can limit downside risk—only incurring the permit cost if the project remains unattractive at the decision point. Finally, (Najafi & Talebi, 2021) develop a LSM real options model to assess the value of deferring investment in a VVER-1000 nuclear power plants (small modular reactors) in developing countries. The study shows that under high electricity price volatility, postponing investment and keeping the option alive can significantly improve project attractiveness compared to traditional DCF methods, especially when the option's validity extends up to 11 years.

Real options in the nuclear energy field

In the field of nuclear energy, real options have been used to evaluate the strategic value of early technological developments, as well as the modularity of new reactor concepts. Épaulard and Gallon, 2001 evaluated the early investment in EPR technology as a strategic option, arguing that its flexibility acts as insurance against future gas price volatility, even considering the uncertainty around its deployment at the time. Gollier et al., 2005 compare large-scale nuclear plants with modular SMRs, showing that modularity provides an option value by enabling staged investment in response to electricity price uncertainty. Similarly, the modular construction of SMRs is analyzed in Jain et al., 2013, who show that sequential investment strategies offer economic resilience under electricity price uncertainty and construction constraints. The operational flexibility of SMRs is also explored in Locatelli et al., 2015. Using the real options framework, the authors assess cogeneration applications for load-following and find that desalination is a viable complement that enhances economic performance under fluctuating demand.

Advanced reactor technologies are also considered in Taverdet-Popiolek and Shoi, 2017, where the authors evaluate the value of investing in Generation IV fast reactors research today, given potential deployment under high uranium price scenarios. Their ROA model supports continued investment despite current competitiveness concerns. Finally, Hampe and Madlener, 2012 apply ROA to High-Temperature

Reactors (HTRs) for industrial cogeneration, calculating both the value of waiting before investing in such technology, and the option to switch operational modes between cogeneration and electricity-only production, with and without switch costs. Their findings underscore the strategic value of HTRs in energy-intensive industries, particularly under volatile electricity prices.

2.3 Contributions

This paper aims to contribute to the literature examining the role of Small Modular Reactors in industrial heat decarbonisation by exploring the economic interest for industrial sites of using a SMR to provide heat for their processes. While previous economic studies on the matter have, to the best of our knowledge, mainly focused on evaluating levelised cost targets to make SMR heat competitive with conventional technologies, our contribution lies in considering irreversibility of ivnestments and risk aversion when modelling the joint decision-making process of an industrial firm and an SMR firm. To achieve this, we use the real options framework in a dynamic programming approach, building a two-agent joint-decision model with multidimensional stochasticity.

3 Modeling methodology

In this section, we present step-by-step the construction of the coupled investment-decision model. We first describe the two-agent set-up used (in Section 3.1). We then detail the mathematical formulation of the multi-dimensional two-agent real option problem adressed (Section 3.2). Finally, we describe the Least-Square Monte-Carlo method used to solve the problem (Section 3.6).

3.1 Set-up and general description of the model

We consider two agents each acting rationally to take their investment and contracting decisions: an industrial firm consuming heat and electricity in its process, and a SMR firm deciding on whether to invest or not in a cogeneration SMR. Figure (1) summarizes the technological and/or bilateral contracting choices available to both firms.

Industrial firm: The industrial firm consumes both heat (Q_h) and electricity (Q_e) for its process. At initial stage, the industrial firm uses a heat-only boiler to produce the heat it needs from natural gas combustion, and source its electricity from the grid. Therefore, in the initial stage, the firm is exposed to fluctuations in both the gas (P_f) and electricity (P_e) prices. The industrial firm can choose to stay with its current equipment, or it can choose to invest in new, self-operated, on-site generation units to produce the heat and electricity required for its processes. The firm has the option to install a cogeneration unit (CG) fuelled by gas to produce heat and electricity for its processes. By doing so, the firm would no longer need to buy electricity from the grid, thus eliminating its exposure to fluctuations in electricity prices, at the cost of an initial investment in the cogeneration unit. In addition, the firm can choose to upgrade its gas burner ($HO-CCS$) or cogeneration ($CG-CCS$) units with a CCS module to lower its net emissions, which brings savings by lowering the emission cost. The industrial firm also has the option of entering into a bilateral contract with the SMR firm for a fixed-price supply of heat (BCh), in which case the firm would still need to purchase electricity from the market. Finally, the industrial firm can decide to enter into a bilateral contract with the SMR firm for heat-and-electricity ($BChe$). In the latter case, exposure to commodities market prices fluctuations would be eliminated entirely.

SMR firm: The SMR firm has three options. It can invest in and build the SMR and sign a bilateral contract with the industrial firm for heat supply (BCh), it can invest and sign a bilateral contract with the industrial firm for heat-and-electricity supply ($BChe$), or it can decide not to invest in the SMR if the project is not economically viable.

We assume that at the time both firms make their decisions the SMR technology has already been demonstrated, and that the project is technologically mature. The cost of SMR is assumed certain, and the availability of the technology to supply both electricity and heat is assumed to be certain.[3] Future research can expand this study and tackle the question of technology uncertainty. Moreover we assume that the industrial site demand is constant in the year so that operational constraints can be taken out of our scope. We finally assume that the SMR capacities align with the consumption quantities of the

[3] *Note to the reviewers*: We are think of refining this in a future version of the paper, by making this cost stochastic.

industrial site in terms of heat supply, i.e that it is designed to produce Q_h of heat. Situations in which the SMR capacity does not align with industrial firm consumption (e.g. where the SMR has to sell part of its power production to the grid anyway) will not be addressed here. However, we assume that the SMR electrical power production capacity is above, but not necessarily equal to the industrial firm power demand.

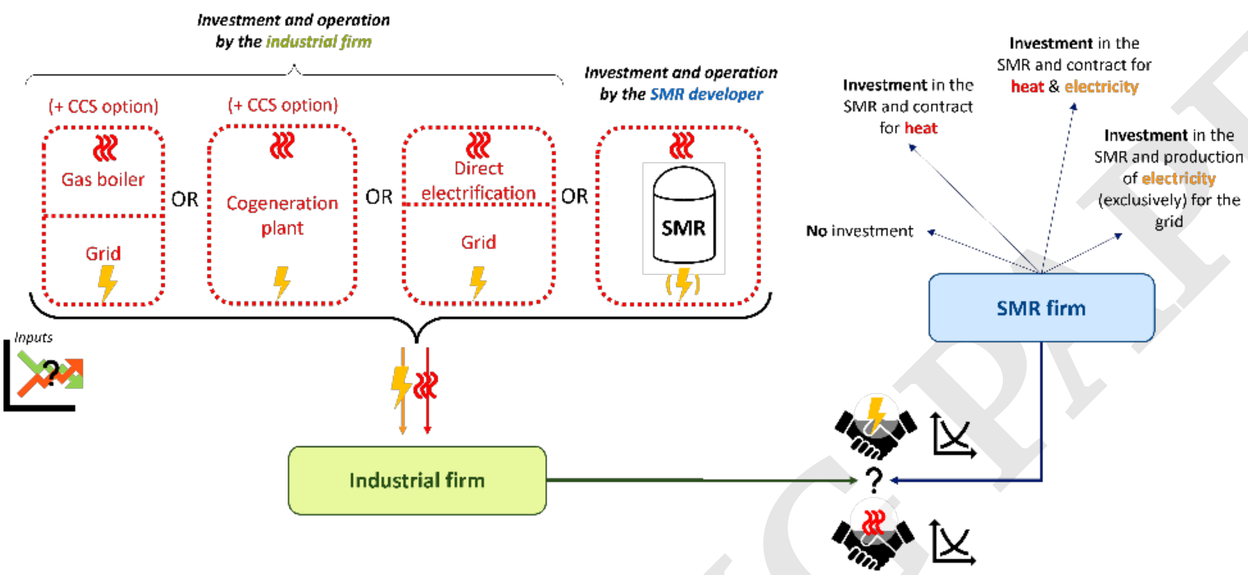


Figure 1: General model set-up

3.2 Formulation of the problem

Consider the perspective of an industrial firm in year t (with t in $[t_0, t_0 + T]$) whose existing heat production equipment, a heat-only gas boiler with efficiency η_{HO}, is expiring. The firm has to make a decision between:

- Keeping its existing equipment (choice labeled HO) until expiration.
- Adding CCS on top of its existing equipment (choice labeled $HO - CCS$).
- Renewing its energy infrastructure by investing in an on-site cogeneration gas boiler (choice labeled CG) with efficiencies $\eta_{CG,h}$ for heat production and $\eta_{CG,e}$ for electricity production.

- Renewing its energy infrastructure by investing in an on-site cogeneration gas boiler with CCS (choice labeled $CG-CSS$).
- Contracting with the SMR firm for Q_h Megawatts of heat supply at constant price for a duration of T_c (choice labeled BCh).
- Contracting with the SMR firm for Q_h Megawatts of heat supply and Q_e Megawatts of electricity supply at constant price for a duration of T_c (choice labeled $BChe$).

The SMR firm has the choice between:

- Not investing
- Investing in the SMR and contracting with the industrial firm for Q_h Megawatts of heat supply at constant price for a duration of T_c. The additional electricity available (Q_e^{smr}) is sold to the grid. This choice is labeled BCh
- Investing in the SMR and contracting with the industrial firm for Q_h Megawatts of heat supply and Q_e Megawatts of electricity supply at constant price for a duration of T_c. The additional electricity available ($Q_e^{smr}-Q_e$) is sold to the grid. This choice is labeled $BChe$.
- Investing in the SMR in a pure electricity generation mode, and producing exclusively electricity for the grid. Taking a full cycle efficiency of η_{SMR} for the production of electricity, transfering the full thermal power of the SMR into the turbo-alternator group makes it produce: $\eta_{SMR}Q_{full}^{smr}$ of electricity. This choice is labeled ELE.

We write $\mathscr{A}_{ind,sep}=\{HO,CG,HO-CCS,CG-CCS\}$ the separate investment choices available to the industrial firm, $\mathscr{A}_{smr,sep}=\{ELE\}$, and $\mathscr{A}_{joint}=\{BCh,BChe\}$ the joint investment and contracting decicions between the industrial firm and the SMR firm.

Following the optimal strategy, the industrial firm will choose the option that maximizes its expected value in year t_i. If the industrial firm was taking its decision independently from the SMR firm decision (i.e, the choices available are the ones from $\mathscr{A}_{ind,sep}$ solely), the value maximization would write:

$$V_{t_i}^{ind,sep}(X_{t_i})=\max\left[\max_{a\in\mathscr{A}_{ind,sep}}\mathbb{E}_{t_i}[NPV_a^{ind}|\,X_{t_i}]\quad,\quad\Phi_{t_i}^{ind}(X_{t_i})\right]\tag{1}$$

Similarly, if $\mathscr{A}_{smr,sep}$ is the set of options available to the SMR firm independently of the decision of the industrial firm, we can write the value maximisation problem from the SMR firm perspective as:

$$V_{t_i}^{smr,sep}(X_{t_i}) = \max\left[\max_{a\in\mathscr{A}_{smr,sep}} \mathbb{E}_{t_i}[NPV_a^{smr} \mid X_{t_i}] \quad , \quad \Phi_{t_i}^{smr}(X_{t_i})\right] \tag{2}$$

However, we now add the two contracting options ($\mathscr{A}_{joint}$) to the industrial firm available choices. The two firms' decisions are coupled in the sense that a bilateral contract can only be signed at a given strike price if it maximises value for both firms. To model the behavior of both firms in the negociation process over a possible heat or heat-and-electricity supply contract, we assume a collaborative behavior. Therefore, we represent the process of both firms bargaining in year t over a strike price with a *Nash bargaining problem*.[4] The complete value-maximization of both the industrial and the SMR firm can then be written:

$$V_{t_i}^{ind}(X_{t_i}) = \begin{cases} V_{t_i}^{ind,sep}(X_{t_i}) & \text{if } TV_t < V_{t_i}^{smr,sep}(X_{t_i}) + V_{t_i}^{ind,sep}(X_{t_i}) \\ 1/2 \cdot (TV_t - V_{t_i}^{smr,sep}(X_{t_i}) + V_{t_i}^{ind,sep}(X_{t_i})) & \text{otherwise} \end{cases} \tag{3}$$

$$V_{t_i}^{smr}(X_{t_i}) = \begin{cases} V_{t_i}^{smr,sep}(X_{t_i}) & \text{if } TV_t < V_{t_i}^{smr,sep}(X_{t_i}) + V_{t_i}^{ind,sep}(X_{t_i}) \\ 1/2 \cdot (TV_t + V_{t_i}^{smr,sep}(X_{t_i}) - V_{t_i}^{ind,sep}(X_{t_i})) & \text{otherwise} \end{cases} \tag{4}$$

with

$$TV_t = \max_{a\in\mathscr{A}_{joint}} \mathbb{E}_{t_i}[NPV_a^{ind} + NPV_a^{smr} \mid X_{t_i}] \tag{5}$$

It should be noted that, under this formulation, the net present values calculated in the $a \in \mathscr{A}_{joint}$ cases do not include the contract cash flows, since the total value used to compute the Nash product is the cumulative value of the two collaborating firms. The contract price can however be derived from the

[4]On this matter, other bargaining equilibriums could be considered. In the case of a real options framework, see for example (Banerjee et al., 2014) for a coupling with a Nash bargaining problem. See Appendix B for a more detailed discussion on our modelling choice for the bargaining step

result of the Nash bargaining problem when an agreement is possible (i.e the bottom cases for Equations (3) and (4)).

In the Section 3.3, we detail the formulation of the reward R_a for each investment and contracting decision for both the industrial firm and the SMR firm. Moreover, the continuation value in year t (written Φ_t^i) can be expressed as the discounted value of the expected future value if no investment or contracting decision is taken in year t, plus the cash flow of keeping running the initial equipment (in the case of the industrial firm, we consider that it is running an on-site boiler until it is replaced). Therefore we write:

$$\Phi_{t_i}^k(X_{t_i}) = e^{-\rho(t_{i+1}-t_i)}\mathbb{E}_{t_i}[V_{t_{i+1}}^k] - CF_{init}^k(t_i) \quad \text{, for } k \in \{ind, smr\} \tag{6}$$

From a pure theoretical perspective, the real options problem described with Equations (3), (4), and (6) can be solved with stochastic dynamic programming. The expression of $V_{t_{i+1}}^k$ in Equation (6) can be replaced with the expression given in Equations (3) and (4), and so on. However, the problem becomes rapidly intractable in practice due to the number of branches and nodes an explicit representation of the decision tree would have. In Section 3.6, we describe how we approximate this stochastic dynamic programming problem with the Least Square Monte-Carlo algorithm.

3.3 Net Present Value formulations

Following the usual assumptions from the Real options literature, we assume the commodity prices to follow a geometric Brownian motion.[5] We write:

$$\frac{dP_f(t)}{P_f(t)} = \mu_f dt + \sigma_f dA(t) \tag{7}$$

$$\frac{dP_e(t)}{P_e(t)} = \mu_e dt + \sigma_e \rho_{fe} dA(t) + \sigma_e \sqrt{1-\rho_{fe}^2} dB(t) \tag{8}$$

Where A and B are two uncorrelated standard Brownian motions, μ_f (resp. μ_e) is the constant drift

[5]This choice is convenient for analytical tractability, even though it might present limits. See (A. S. Siddiqui & Maribu, 2009) for a discussion on these limits.

of P_f (resp. P_e), and σ_f (resp. σ_e) is the constant volatility of P_f (resp. P_e). Coefficient ρ_{fe} is the correlation between P_f and P_e. We write P_{CO_2} the price of CO_2 (assumed perfectly known), [6] and e_{tech} the emission factor of technology $tech$ (in t_{CO_2}/MWh). Factors $\eta_{tech,h}$ and $\eta_{tech,e}$ are the efficiencies of technology $tech$ for producing heat and electricity. Π is the annual benefits made by the industrial firm. I_{tech} is the upfront investment cost for technology $tech$. T_{tech}^{build} and (resp. T_{tech}^{life}) correspond to the construction time (resp. lifetime) of technology $tech$.

Finally, we introduce $K(\mu, t_0, t_1) = \frac{e^{(\mu-\rho)t_0} - e^{(\mu-\rho)t_1}}{\rho-\mu}$, $K_{CO_2}(e, t_0, t_1) = \int_{t_0}^{t_1} e \cdot P_{CO_2}(t)dt$ and $\Pi_{tech} = \Pi \cdot K(0, 0, T_{tech}^{build} + T_{tech}^{life})$ to write NPV expressions more concisely.

The Net Present Values for both the industrial and the SMR firm can then be formulated.

On-site heat-only boiler (HO)

The cash flow for the industrial firm on if it keeps its on-site heat-only boiler (without upgrading) is:

$$CF_{init}^{ind}(t) = \Pi - Q_h^{ind} \cdot \left(P_f(t) + e_{HO}P_{CO_2}(t)\right) - Q_e^{ind} P_e(t) \tag{9}$$

On-site cogeneration unit (CG)

$$\begin{aligned} NPV_{CG}^{ind}(t) = \Pi_{CG} - I_{CG} - \frac{Q_h^{ind}}{\eta_{HO}}\left(P_f(t)K(\mu_f, 0, T_{CG}^{build}) + K_{CO_2}(e_{HO}, 0, T_{CG}^{build})\right) - Q_e^{ind} P_e(t) K(\mu_e, 0, T_{CG}^{build}) \\ -\left(\frac{Q_h^{ind}}{\eta_{CG,h}} + \frac{Q_e^{ind}}{\eta_{CG,e}}\right)\left(P_f(t)K(\mu_f, T_{CG}^{build}, T_{CG}^{build} + T_{CG}^{life}) + K_{CO_2}(e_{CG}, T_{CG}^{build}, T_{CG}^{build} + T_{CG}^{life})\right) \end{aligned} \tag{10}$$

On-site cogeneration unit combined with CCS (CG-CCS)

[6] *Note to the reviewers*: we wish to refine this in a future version of the paper to account for the huge uncertainty on the future CO_2 prices (e.g, the ones coming from the EU-ETS.

$$NPV^{ind}_{CG-CCS}(t) = \Pi_{CG-CCS} - I_{CG} - I_{CCS} - \frac{Q^{ind}_h}{\eta_{HO}}\left(P_f(t)K(\mu_f, 0, T^{build}_{CG}) + K_{CO_2}(e_{HO}, 0, T^{build}_{CG})\right) - Q^{ind}_e P_e(t)K(\mu_e, 0, T^{build}_{CG})$$
$$-(\frac{Q^{ind}_h}{\eta_{CG,h}\eta_{CCS}} + \frac{Q^{ind}_e}{\eta_{CG,e}\eta_{CCS}})\left(P_f(t)K(\mu_f, T^{build}_{CG-CCS}, T^{build}_{CG-CCS} + T^{life}_{CG-CCS}) + K_{CO_2}(e_{CG-CCS}, T^{build}_{CG-CCS}, T^{build}_{CG-CCS} + T^{life}_{CG-CCS})\right) \tag{11}$$

Adding CCS on top of on-site heat-only boiler

$$NPV^{ind}_{HO-CCS} = \Pi_{HO-CCS} - I_{CCS} - \frac{Q^{ind}_h}{\eta_{HO}}\left(P_f(t)K(\mu_f, 0, T^{build}_{CCS}) + K_{CO_2}(e_{HO}, 0, T^{build}_{CCS})\right) - Q^{ind}_e P_e(t)K(\mu_e, 0, T^{build}_{CCS} + T^{life}_{HO-CCS})$$
$$-\frac{Q^{ind}_h}{\eta_{HO}\eta_{CCS}}\left(P_f(t)K(\mu_f, T^{build}_{CCS}, T^{build}_{CCS} + T^{life}_{HO-CCS}) + K_{CO_2}(e_{HO-CCS}, T^{build}_{CCS}, T^{build}_{CCS} + T^{life}_{HO-CCS})\right) \tag{12}$$

Direct electrification

$$\begin{aligned} NPV^{ind}_{DE} = \Pi_{DE} - I_{DE} - \frac{Q^{ind}_h}{\eta_{HO}} P_f(t)K(\mu_f, 0, T^{build}_{DE}) - Q^{ind}_e P_e(t)K(\mu_e, 0, T^{build}_{DE}) \\ -(\frac{Q^{ind}_h}{\eta_{DE,h}} + Q^{ind}_e)P_e(t)K(\mu_e, T^{build}_{DE}, T^{build}_{DE} + T^{life}_{DE}) \end{aligned} \tag{13}$$

Bilateral Contrat for heat supply (The NPV calculated here splits in two terms to segregate the bilateral contract revenues and costs from the rest, since this "non-contract" NPV expression ($NPV_{Bch,*}$) is used in the Nash bargaing problem to find the optimal strike price of the contract)

$$\begin{aligned} NPV^{ind}_{BCh} &= NPV^{ind}_{BCh,*} \\ &= \Pi_{BCh} - \frac{Q_h}{\eta_{HO}} P_f(\tau)K(\mu_f, 0, T^{build}_{SMR}) - Q_e P_e(t)K(\mu_e, 0, T^{build}_{SMR} + T_c) + NPV^{ind}_{BCh,contract} \end{aligned} \tag{14}$$

$$\begin{aligned} NPV^{smr}_{BCh} &= NPV^{smr}_{BCh,*} + NPV^{smr}_{BCh,contract} \\ &= -I_{SMR} + Q^{smr}_e P_e(t)K(\mu_e, T^{build}_{SMR}, T^{build}_{SMR} + T^{life}_{SMR}) + NPV^{smr}_{BCh,contract} \end{aligned} \tag{15}$$

Bilateral Contrat for heat-and-electricity supply

$$\begin{aligned} NPV^{ind}_{BChe} &= NPV^{ind}_{BChe,*} + NPV^{ind}_{BChe,contract} \\ &= \Pi_{BChe} - \frac{Q_h}{\eta_{HO}} P_f(\tau) K(\mu_f, 0, T^{build}_{SMR}) - Q_e P_e(t) K(\mu_e, 0, T^{build}_{SMR}) + NPV^{ind}_{BChe,contract} \end{aligned} \tag{16}$$

$$\begin{aligned} NPV^{smr}_{BChe} &= NPV^{smr}_{BChe,*} + NPV^{smr}_{BChe,contract} \\ &= -I_{SMR} + (Q^{smr}_e - Q_e) P_e(t) K(\mu_e, T^{build}_{SMR}, T^{build}_{SMR} + T_c) + Q^{smr}_e P_e(t) K(\mu_e, T^{build}_{SMR} + T_c, T^{build}_{SMR} + T^{life}_{SMR}) + NPV^{smr}_{BChe,contract} \end{aligned} \tag{17}$$

Here the underlying hypothesis is that the electricity that is sold to the industrial firm is then redirected to the grid after the contract expires. We make this assumption since the SMR cannot know if the contract will be re-signed after T_c.

SMR investment and electricity production exclusively

$$NPV^{smr}_{ELE} = -I_{SMR} + \eta_{SMR} Q^{smr}_{full} \cdot P_e(t) K(\mu_e, T^{build}_{SMR}, T^{build}_{SMR} + T_c) + NPV^{smr}_{ELE,contract} \tag{18}$$

3.4 Adding stochasticity on the SMR cost and build time, and on CO2 prices

Ongoing work: Coming in future versions

3.5 Adding risk aversion

Ongoing work: Coming in future versions

3.6 Least Square Monte Carlo

The Least Squares Monte Carlo (LSMC) method is a numerical technique used to value real options originally introduced by (Longstaff & Schwartz, 2001) for American option pricing. LSMC combines Monte

Carlo simulation with regression-based estimation of continuation values.In the real options framework, it enables investment decisions to be modelled under uncertainty by simulating the multiple paths of underlying stochastic variables (here, commodity prices) and using least squares regression to approximate the conditional expected value of future payoffs at each decision timestep. The latter is the key feature of the LSMC method and enables real options simulations with a large number of paths over several timesteps to be run without falling into the curse of dimensionality. Rather than simulating a full decision tree with $\mathscr{W}$ new branches at each timestep $t \in \mathscr{T}$ and solving backward for the $\mathscr{T}^{\mathscr{W}}$ decision nodes, the LSMC only simulates $\mathscr{W}$ Monte Carlo paths from the original node (i.e. the initial timestep) and uses statistical polynomial regression to estimate the continuation value at each decision node (w, t) while still using information from the entire $\mathscr{W}$ set of simulated underlying paths.

A detailed description of the LSMC algorithm in the context of energy planning can be found in (Pringles et al., 2015) where they apply the real options framework to power transmission grid investments. In terms of mathematical modeling compared to (Pringles et al., 2015), we change the optimal strategy step (which for them corresponds to comparing the continuation value to the maximum value of exercicing the different investment options), by our optimal strategy described by Equations (3), (4), and (6).

4 Data

In this section, we describe the data used to apply the Real Options model to several real-world cases. We model the decision making of both firms on a 15 year horizon from 2035 to 2050.

Commodity demand and prices: We take our real-world case from the chemical industry, and assume the demand of the industrial firm to be $Q_h^{ind} = 876$GWh per year and $Q_e^{ind} = 292$ GWh per year, which would correspond to a ribbon consumption of 100 MW of heat and 33 MW of electricity (to have the electricity representing one fourth of the site energy demand) [7]. In fact, this consumption corresponds more to the aggregated consumption of an industrial hub, which we decide to model has one

[7] See (**mallapragada_decarbonization_2024**) for the breakdown of energy demand between heat and electricity for the various industrial sectors.

deciding entity for the simplicity of modelling and results analysis.

Moreover, we assume the SMR capacity to be $Q_h^{smr} = 876$ GWh of heat and $Q_e^{smr} = 527$ GWh of electricity per year.[8] Therefore, even in the case of a bilateral contracting between the firms for heat and electricity supply, part of the production of the SMR is sold to the grid at price P_e.

The gas and electricity prices are assumed to follow a Geometric Brownian Motion, with initial values, drift and volatility values given in Table 1. The CO_2 prices are assumed to grow from 80 to 500 €/tCO_2 between 2035 and 2050.[9] Contrary to gas and electricity prices, we do not model stochasticity on CO_2 prices in this first version of the paper.

The duration of the contracts the SMR and industrial firm can agree on (T_c) is set to 20 years.

Table 1: Fuel prices parameters

	Drift * (μ)	Volatility ** (σ)			Initial value ***		
	Mid case	Low case	Mid case	High case	Low case	Mid case	High case
Gas (P_f)	0	0	0.3	0.45	30	40	60
Electricity (P_e)	0.015	0.15/2	0.15	0.3	40	60	90

* (Cret et al., 2024) and calculation on 2014-2020 French prices history

** Calculation on 2014-2020 French prices history

*** Mid scenario is calibrated on France's 2025 prices

Technology parameters: Efficiencies, GHG emission intensity, lifetime and investment costs for the different technologies are summarized in Table 2. Yearly fixed operating and maintenance costs are included in the values of investment costs considered. The investment cost for CCS upgrades is taken as 5 M€/tCO_2/h, and the efficiency of capture is assumed to reach 90%.[10] In addition, the efficiency degradation due of the unit when adding CCS (due to the additional gas consumption needed to fuel the CCS process) is taken at $\eta_{CCS} = 80\%$. Finally, we assume the existing on-site boiler to expire in 2050, 15 years after the beginning of the simulation horizon.

[8]We assume a core nameplate capacity of 330MW_{th}, a load factor of 0.83, and a 30% conversion efficiency from core power to electric power (see (Vanatta et al., 2023)). The electric nameplate power if it produces 100MW_{th} on average is 67MW_e, which gives a yearly production of 587GWh_e when assuming a 0.9 load factor. The

[9]See hypotheses from Enerdata scenarios made with the POLES model at https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html

[10]We use data from (Tautorat et al., 2025)

Table 2: Technologies parameters

	Investment Cost * (€/kW)	Lifetime ** (yr)	Efficiency *** (Heat & Elec)	GHG intensity **** (tCO_2/MWh)	Build time (yr)
On-site gas boiler	-	20	0 & 0.9	0.3	1
On-site gas cogeneration	800	20	0.5 & 0.36	0.3	1
Direct electrification	500	20	0.9 & 1	-	1
SMR	5000	60	-	0	5

* (Tautorat et al., 2025)(Vanatta et al., 2023)
** (Tautorat et al., 2025)(Vanatta et al., 2023)(Lindroos et al., 2019)
*** (Tautorat et al., 2025)(Pursiheimo et al., 2022)(Madeddu et al., 2020)
**** (Only direct emission accounted). Before applying efficiency. Source: (RTE & ADEME, 2021)

Least Square Monte Carlo parametrization: We use polynomial basis functions for the regression step of the form: $P_f^n \cdot P_e^m$ with n and m integers such that $n+m \leq 4$. We use 100 000 Monte Carlo paths to solve the LSM. Solving the model for one set of paramaters takes around 45 minutes on a 64 core AMD Genoa9354 3.25GHz. Additional parallelization of the code could make it faster to run.

5 Results

In this section, we detail the results obtained on the real-world cases described in section 4. We first describe the results obtained in the median scenario, before conducting sensitivity analysis on the commodity prices, their volatility, and on the SMR capital expenditure.

5.1 Median scenario

Figure (2) depicts for each firm the probabilities of each decision being taken at or before year t, for the median case described in Section 4. On the upper two subfigures, these probabilities are obtained as a result of the real options problem solved with Least Square Monte Carlo. On the lower two subfigures, we plot these same probabilities in the case where the information gains component of the continuation value is set to zero, which goes back to considering only the immediate expected return of a decision when choosing to invest or contract, and not valuing the option to wait. We can then compare for each firm how the irreversibility has impacted the optimal investment and contracting decision.

It is important to note that we voluntarily removed the last year of simulation from the figures to avoid the border effect of the horizon end. Indeed, at the horizon end, no possibility is given to the industrial firm to wait another timestep, and an investment decision to replace the on-site boiler has to be made. As we are only interested in exploring the effect of the continuation value on the investment decisions probabilities, we therefore choose to remove the final year in our plots. Note also that contrary to the industrial firm, the SMR firm can always wait, even at the last timestep, which corresponds to the "not investing" option.

In the median scenario, we observe that, when sticking to the simple NPV analysis (i.e, assigning a value of zero to the information gains component of the waiting value), the probability that the optimal decision for both firm is to agree on a bilateral heat supply contract reaches around 70% by 2040. However, when the irreversibility of the investment and contracting decisions of both firms is accounted for, the "waiting" region increases significantly for both firms. This is due to two complementing effects: On the industrial firm side, the uncertainty about future gas and electricity prices makes the continuation value higher than the expected NPV of investment options available to the firm. Similarly, the SMR firm will see its continuation value increase due to the uncertainty in electricity prices (affecting the electricity selling gains component of the NPV). As a result, the bargaining step of the strike price is streched in two opposite directions by the accountness of irreversibility. The SMR firm requires a higher strike price to cover the uncertainty of its capital expenditure recovery, while the industrial firm asks for a lower strike price otherwise it will stick to the "waiting" option and get the continuation value. We can observe that in the simple-NPV case, the probability of agreement over time is concave, i.e there is less and less Monte Carlo paths where the contracting decision becomes economically interesting, while it is convex in the real options case. The revealig of additional information (valued by agents due to investments and contracts irreversibility) makes it more and more interesting to agree on a heat supply contract.

Aside from the decrease in the attractiveness of the bilateral heat supply contract, we also observe that the probability of the SMR firm investing in electricity production for the grid has decreased. Generally speaking, the SMR firm's decision to invest alone is driven by the industrial firm's low strike price (because there are relatively interesting non-SMR options), which cannot compete with the profits the

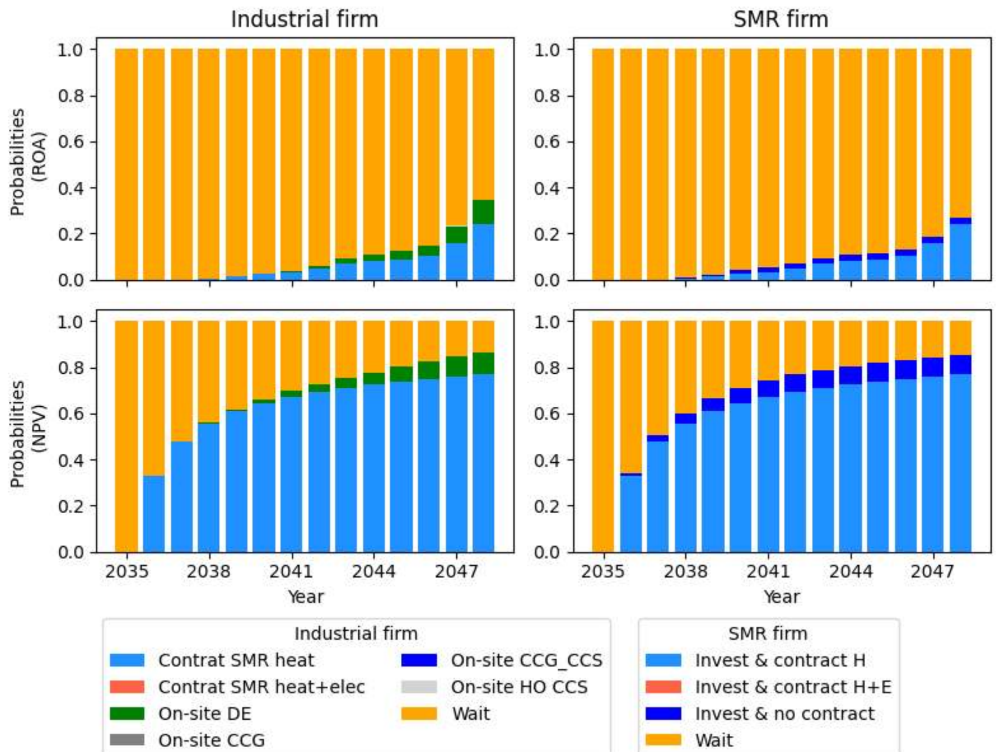


Figure 2: Probability of investment decision for each firm in the *median* case

SMR firm can earn by converting 100% of its available thermal power to electricity and selling it on the market. In the real-options case, however, the "Investing alone" option does not create enough benefits to outweigh the continuation value resulting from the electricity price uncertainty, which translates into the probability of this option dropping to almost zero.

It is important to note that while the contract for heat and electricity is an option available to both firms, it doesn't appear here beause in a risk-neutral case it is strictly equivalent in terms of value to the heat-only contract. Indeed, if both firms agree to a heat-only bilateral contract, upgrading to a heat-and-electricity supply contract simply cancels out the industrial firm's new gains (from not buying electricity from the grid) with the SMR firm's additional losses (from not selling the same amount of electricity back to the grid at the same price) in the total value expression for the Nash bargaining stage. However, when risk aversion will be added in a future version, intuition suggests that, to hedge against market price volatility, the risk-averse SMR firm will agree to a contract at a lower strike price than it would have asked for in a risk-neutral setting. Meanwhile, the risk-averse industrial firm will agree to sign a bilateral contract at a higher strike price than it would have agreed to in a risk-neutral setting. Therefore, we anticipate the agreement region growing under risk aversion, thus cancelling part of the 'irreversibility' effect.

Moreover, when the irreversibility of investments is taken into account, the probability of the industrial firm investing in direct electrification decreases slightly, but in a lower proportion compared to the contracting option. Direct electrification indeed involves lower capital expenditure than the SMR solution, while still enabling the CO_2 price to be offset. Finally, as far as gas cogeneration or CCS solutions are concerned, they only emerge marginally, even when not valuing the continuation option – their proportion is so small that it cannot be seen on Figure 2).

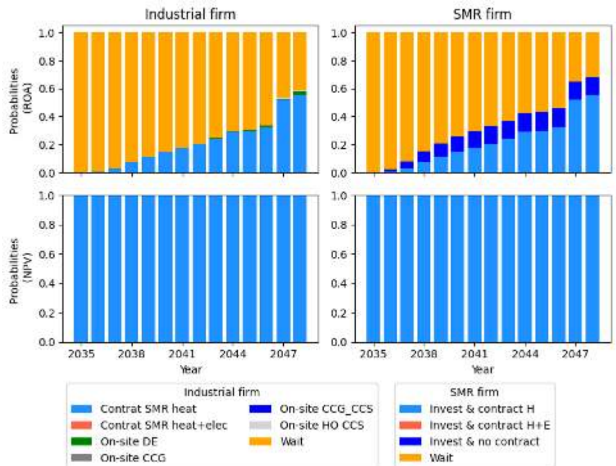
5.2 Sensitivity analysis

Sensitivity to SMR Capital Expenditure

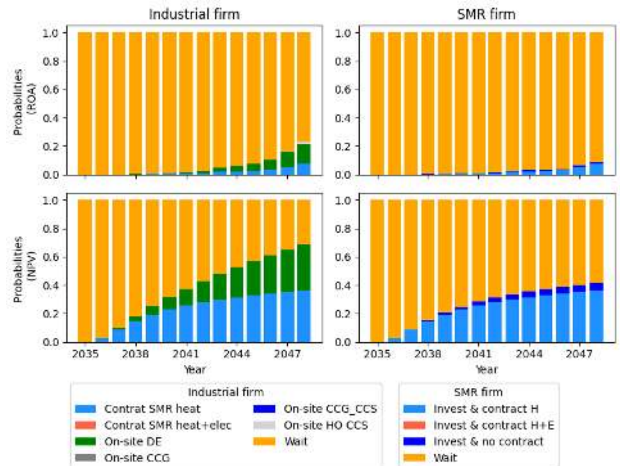
The median investment cost of the SMR was set at 5000€/kW$_e$ (taking the pure electrogeneous operation as the power reference). Given the high uncertainty on the target investment cost these technologies will be able to reach by 2035, we move add four sensitivity cases to our analysis, with the investment cost decreases by 30% compared to the median value, increased by 30%, increased by 50%, and doubled. These scenarios are plotted on Figure (3)

As one could expect, the decrease of the SMR investment cost makes it more attractive and thus increases the probability that both parties agree on a bilateral contract for heat supply. At the same time, it is interesting to note that the simple NPV method gives a nearly 100% probability of agreement between the two firms, and that, as a result, the irreversibility leaves some room to the "invest alone" region on the SMR side (compared to its absence in the simple NPV case), even if it remains limited in magnitude.[11] On the opposite, as a result of investment costs increase, the industrial firm turns to direct electrification to meet its heat demand. In addition, under these high investment cost assumptions, some scenarios exhibit CCS investment in 2048.

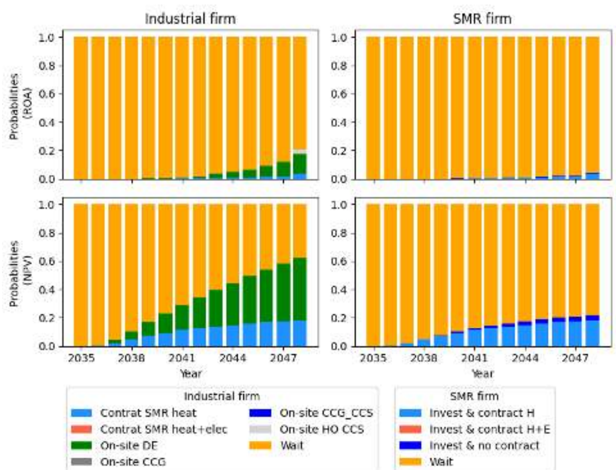
[11] Said differently, there are cases in the real option setting where an agreement is not the best solution for the SMR firm, because investing alone and producing only electricity generates more value, while this doesn't happen when the information-revealing value is set to zero.



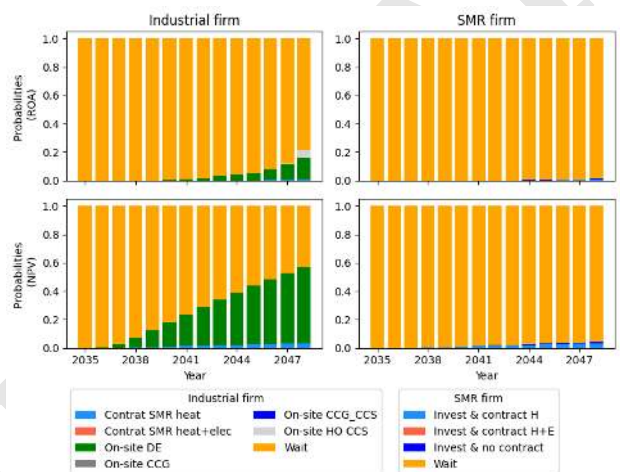
(a) Investment cost -30% compared to median scenario



(b) Investment cost +30% compared to median scenario



(c) Investment cost +50% compared to median scenario



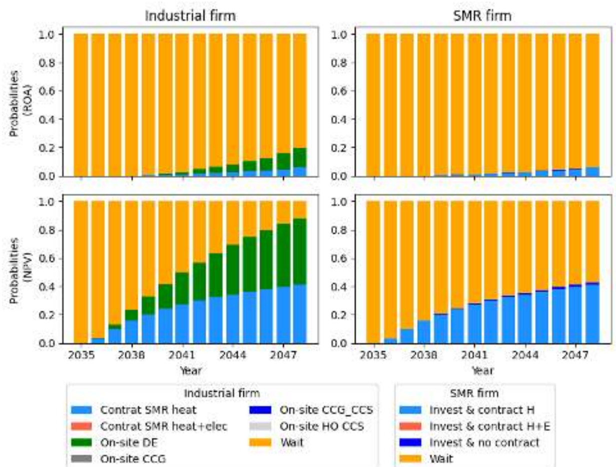
(d) Investment cost doubled compared to median scenario

Figure 3: Sensitivity of decision probabilities to SMR investment costs. Upper row of each subfigure corresponds to decisions probabilities of each firm obtained with the real-options method. Lower row of each subfigure corresponds to decisions probabilities obtained with the simple NPV method.

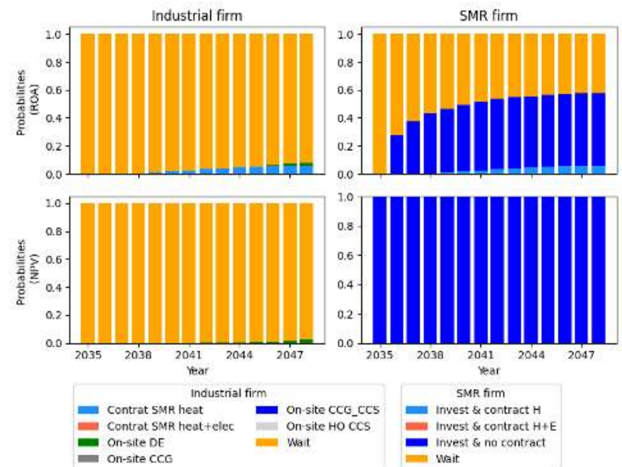
Sensitivity to commodity prices parameters

We plot on Figure (4) the sensitivity of the simple NPV and the real-options analysis output probabilities for different levels of initial (2035) gas and electricity prices. Low and high levels of electricity prices correspond respectively to 40 and 90€/MWh, while low and high levels of gas prices correspond respectively to 30 and 60€/MWh. In this setting, the volatilities are set to their median value. We observe that a drop in both gas and electricity prices to their low value has a similar effect to the +30% SMR Capex scenario, in terms of probability of agreement on a bilateral contract for heat supply. When gas prices are low and electricity prices are high, the SMR asks for a higher strike price in the bargaining with the industrial firm, because its reservation value is increased by the increased value of selling its full power in the form of electricity to the grid. Thus, the agreement region shrinks. On the opposite, when gas prices are high and electricity prices are low, both parties have an higher interest in signing a contract, because the gas-based options for the industrial firm are more expensive, and the SMR firm asks for a lower strike price when comparing the agreement value to the "Invest alone" value. We also note that in this case, direct electrification represents also abaout a third of the investment probability in 2050, due to the cheap electricity available to the industrial firm. Finally, when both gas and electricity initial prices are in their high end, the firms have a 100% chance to agree.

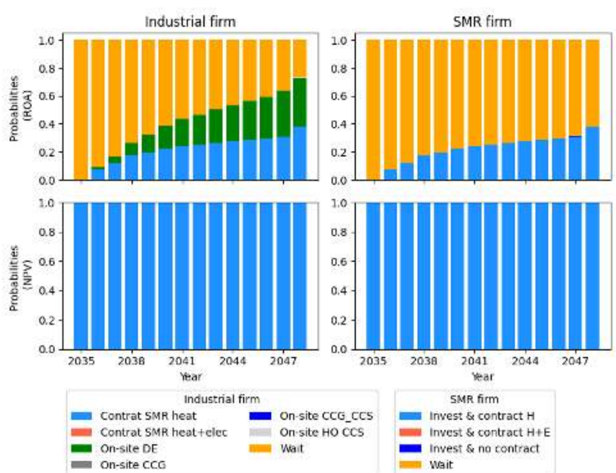
In addition to the initial commodity price levels sensitivity, we plot on Figure (5) the sensitivity of the decision probabilities to the price volatilities. First, we observe that, compared to the median scenario (Figure (2)), a simultaneous low volatility on both commodity prices delays the investment and/or contracting timing to the very final year (not represented on the graph). In the simple-NPV case with low volatilities, we observe a strong appeal for the contractualisation solution. Second, when both volatilities are high, the contract signing probability lowers compared to the median case, and is transfered to an increased "Invest alone" region from the SMR side. The firm "waiting" region in fact almost don't change, but separate decisions are prefered. Finally, when gas prices volatility is high and electricity prices volatility is low, we observe a very slight increase in the contracting probability, and the almost disappearance of the "direct-electrificationé region on the industrial firm side, and of the "invest alone" region on the SMR firm side. A low gas prices volatility coupled to a high electricity prices volatility has the opposite effect. It is also interesting to note that in this last case, the "waiting" region is decreased on the industrial firm side and increased on the SMR firm side.



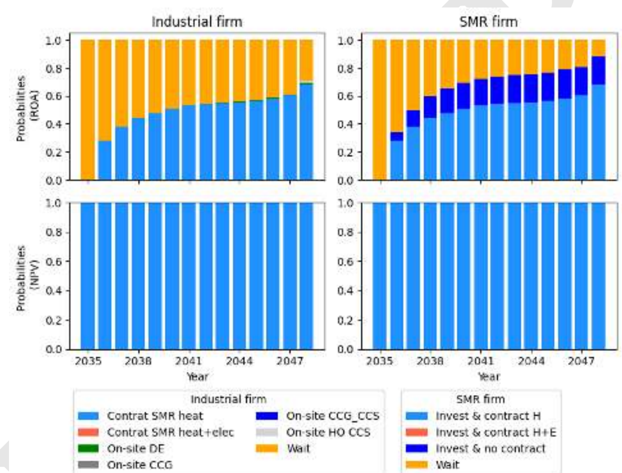
(a) Low P_f and Low P_e



(b) Low P_f and High P_e



(c) High P_f and Low P_e

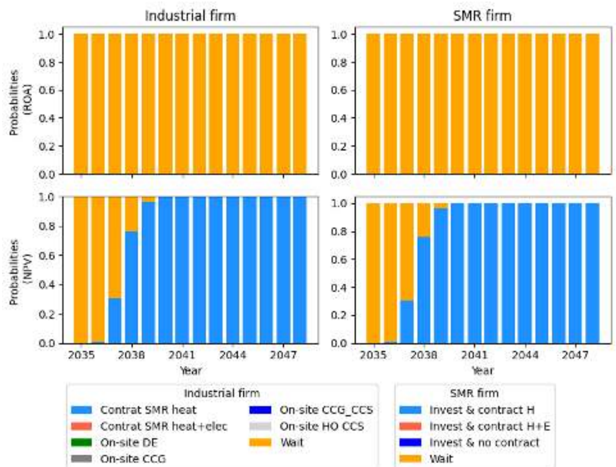


(d) High P_f and High P_e

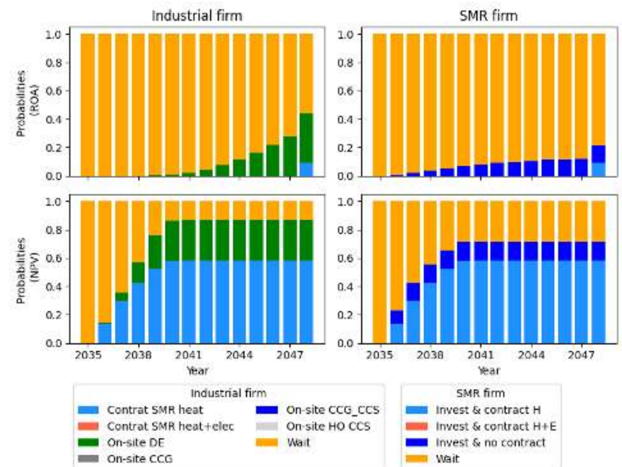
Figure 4: Sensitivity of decision probabilities to initial (2035) commodity prices. Volatilities are set to their median values.

6 Conclusion

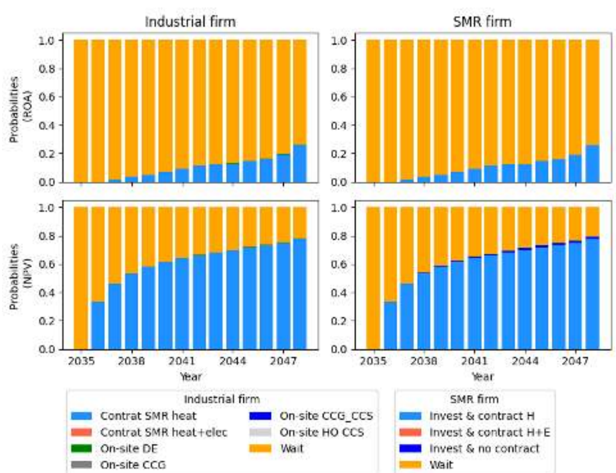
In this paper, we examined the investment and contracting decision-making processes surrounding the deployment of Small Modular Reactors (SMRs) for industrial heat and electricity supply, using a Real Options Analysis framework. By modeling the coupled choices of both industrial firms and SMR developers, we highlight how investment irreversibility, market uncertainty, and contractual terms shape the timing and configuration of decarbonisation pathways in the industrial sector. We include bilateral contracting options in our setting as potential mechanisms to overcome input price volatilities and align



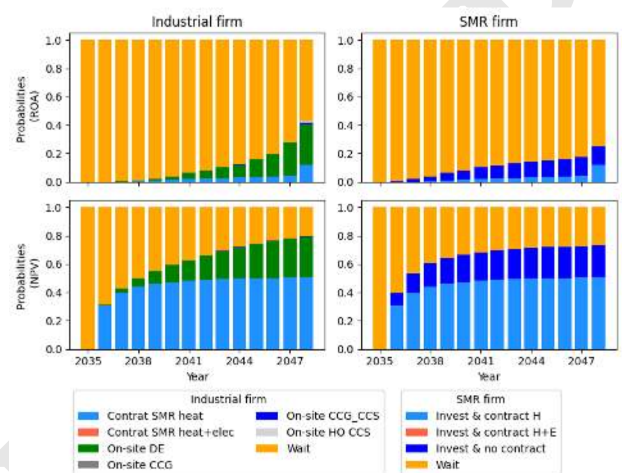
(a) Low σ_f and Low σ_e



(b) Low σ_f and High σ_e



(c) High σ_f and Low σ_e



(d) High σ_f and High σ_e

Figure 5: Sensitivity of decision probabilities to commodity prices volatilities. Initial prices (2035) are set to their median value.

heat supply from an SMR with industrial process heat demand. Our framework captures the value of waiting for information and the cost of irreversibility, offering insights into how industrial firms and SMR firms may react in presence of volatile prices and several investment or contracting options.

We show that accounting for investment and contracting inherent irreversibility in our modeling of both firms decision making, the probability of agreement on a bilateral contract lowers. Second, we analyze how the SMR investment costs hypothesis influences the outcomes of the model. We find that, while higher SMR investment costs make the "waiting" region increase for both firms, direct electrification also grows slightly to replace part of the agreement region. In the case of relatively low SMR investment costs, part of the agreement region is subsituted by the SMR investing alone to produce solely electricity (and supplying it the grid). Finally, we study the sensitivity of our results to the gas and electricity price parameters. These last results should be updated in a risk-averse setting, which will intuitively penalize exposure to uncertainty.

This working paper is at an early stage and needs further work to complete the analysis. In future versions of the paper, the framework used could be improved in different ways:

- We want to study how the results are affected when introducing risk aversion in the firms behavior. For now, the agents represented in our model are risk-neutral, which limit the usefulness of having contracting options to hedge against volatile commodities prices.
- We want to study how the results are affected when introducing stochasticity in CO_2 prices and investment costs.

Appendices

A Nomenclature, variables and parameters

Nomenclature:

$\cdot_h$ = heat, $\cdot_e$ = electricity, $\cdot_f$ = fuel

SMR = Small Modular Reactor

HO = Heat Only boiler

CG = On-site gas Cogeneration

CCS = Carbon Capture and Storage

BCh = Bilateral Contract for Heat

BChe = Bilateral Contract for Heat and Electricity

ELE = Production of electricity only, which is dispatched to the grid

NPV = Net Present Value

Functions:

$V_t^{ind,sep}(X)$	Value of the industrial firm at time t, for underlying X
$\Phi_t^{ind}(X)$	Cotinuation value of the industrial firm at time t, for underlying X
$V_t^{ind,sep}(X)$	Value of the industrial firm in the case where no joint-decision with the SMR firm can be taken
$\Phi_t^{smr}(X)$	Cotinuation value of the SMR firm at time t, for underlying X
$V_t^{smr,sep}(X)$	Value of the SMR firm at time t, for underlying X
$V_t^{smr,sep}(X)$	Value of the SMR firm in the case where no joint-decision with the industrial firm can be taken
NPV_{CG}^{ind}	Net Present Value of the CG investment decision for the industrial firm
NPV_{CG-CCS}^{ind}	Net Present Value of the $CG-CCS$ investment decision for the industrial firm
NPV_{HO-CCS}^{ind}	Net Present Value of the $HO-CCS$ investment decision for the industrial firm
NPV_{BCh}^{ind}	Net Present Value of the BCh decision for the industrial firm
NPV_{BChe}^{ind}	Net Present Value of the $BChe$ decision for the industrial firm
NPV_{BCh}^{smr}	Net Present Value of the BCh decision for the SMR firm
NPV_{BChe}^{smr}	Net Present Value of the $BChe$ decision for the SMR firm
NPV_{ELE}^{smr}	Net Present Value of the ELE decision for the SMR firm

B Nash bargaining approach

The Nash bargaining problem was first introduced in (Nash, 1950), with the following formulation. If two agents A and B have reservations values R_A and R_B that they can obtain without collaborating, and utilities $u_A(x)$ and $u_B(x)$ they can get from agreement x, the optimal agreement on the set of possible agreements S is x^* such that:

$$x^* = argmax_{x \in S} \, (u_A(x) - R_A)(u_B(x) - R_B)$$

This bargaining frameworks assumes, within other assumptions, symmetry of bargaining power between agents. Roth, 1979 then expanded this framework to account for some asymmetry in the bargaining process, and write:

$$x^* = argmax_{x \in S} \, (u_A(x) - R_A)^{\beta}(u_B(x) - R_B)^{(1-\beta)}$$

Where β is a scalar between $[0,1]$ the bargaining power asymmetry. One is also refered to (Binmore et al., 1986) on the modelling of asymmetry sources in bargaining problems, using game theory.

In the context of our paper, we stick to the Nash's formulation of the bargaining problem, with symmetric bargaining power. If we write V the total value to share in a possible agreement between our two firms, and x the share that goes to firm A, and if the utilities are simply the values that firms get from the agreement, we want to find $\hat{x}$ such that:

$$x^* = argmax_{x \in S} \, (x - R_A)(V - x - R_B)$$

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