Title: Robust Carbon Dioxide Utilization Markets
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1. Research Question:

Demands for cheap energy and a cleaner environment seem hard to reconcile. Fossil fuels production in the United States amounts to 73 quadrillion British thermal units (Btu) and is responsible for 4.6 $GtCO_2$. Carbon capture, utilization, and storage (CCUS) has attracted substantial attention as it could allow for the use of cheap fossil fuels while keeping carbon dioxide emissions into the atmosphere in check [11]. Yet, despite its promising contribution to addressing the perils of climate change, CCUS is one of the most underdeveloped technological paths towards deep decarbonization [1]. While the technology itself is straightforward, there are barriers associated with the technical and financial viability of these CCUS projects that hamper their development [14]. These barriers come from four sources: technical capacity [12] and costs [9,22], climate and energy regulatory uncertainty [18,23], increased availability of cheap renewable energy [13], and incipient industrial demand for CO_2 [19, 23]. All these different barriers point to one single outcome: an immature market for the product of the CCUS, namely carbon dioxide (CO_2). The fact remains that we need a CCUS sector with the capacity to deal with approximately 1 $GtCO_2$/year in the United States and around 14% of emissions worldwide. For CCUS to be deployed at an industrial scale commensurate with these climate needs, the product of CCUS cannot be waste disposal alone (i.e., geological sequestration), it needs to add value to society beyond emissions reduction [10]. The stream of CO2 needs to be incorporated in the economy as an input in the production process. With this idea in mind, my main research question is under which regulatory, economic and technical circumstances does a robust market for CO_2 arise and what are the biggest threats to its development?

The main contribution of this work is exploring the market for CO_2 with the goal of envisioning ways to increase the market potential for CCUS. It complements efforts on understanding the barriers in transportations, sequestration and storage [16] and possible solutions to those barriers [25]. My proposed work also relates to the literature on the general equilibrium effects of a carbon tax and its interactions with other taxes in the economy [7]. Unlike the previous literature that concentrates on the distortionary effect of a carbon tax in other markets, here we concentrate on the effects in the market for CO2 as a productive input in the economy [20]. This work also contributes to the literature on the optimal investment in innovation and role of endogenous technological development in climate and environmental policy [2]. Finally, my work adds to the literature on optimal climate policy and the optimal deployment of different climate impact mitigation strategies [5,6,15]. More generally, this work contributes to the CCUS research on social sciences, which until now has been dominated by research in engineering and technology leaving important questions unanswered [8].

2. Methodology

My proposal is to develop an economic framework of the carbon economy. There are three approaches I will develop in the proposed paper. First, in section 2.1, I will consider a static general equilibrium model of a carbon economy to ask questions about market structure, competition and policy. Second, in section 2.2, I will consider a dynamic general equilibrium model to ask questions about the sort of policy interventions that will be required to increase the potential of the carbon economy. Third, in section 2.3, I will consider an integrated assessment model and analyze possible expansion pathways to enable an efficient use of available technological options. Sections 2.2 and 2.3 are based on the results and intuition developed in section 2.1, which is where I spend most of the space allocated in this proposal.

2.1. Static model

I consider an economic environment where firms selling CO_2 interact with potential buyers via transportation infrastructure networks. I refer to carbon dioxide markets in this proposal rather than just simply carbon markets, to distinguish between the markets created by regulatory interventions and markets for the utilization of carbon dioxide, where CO2 is bought and sold in open markets under different degrees of competition. I will borrow from the two-sided markets literature to focus on the role on transportation networks as platforms that enable or curtail competition [21]. I will then explore the interaction between carbon policy and carbon dioxide markets and propose some extensions to the model that allow for investment in pipeline capacity and market expansion via firm entry and exit.

2.1.1. Set-up

CO2-producers: There are many sources of anthropogenic CO_2 that could adopt CCS techniques. Here, I consider the case of coal and natural gas electric power plants as CO_2 suppliers, although the model can be readily expanded to other possible sources of highly localized CO_2 production. The number of firms in the electricity sector is n_E. Power plants outfitted with CCS technology can capture CO_2 incurring a cost $m(a)$ that is increasing and convex in the amount abatement, a. There are two motivations for power plants to capture CO_2. First, they are subject to a carbon tax, $\tau_E \in \mathbb{R}$. Second, they can sell CO_2 to extraction and manufacturing firms that require CO_2 as an input in their production process. Each ton of CO_2 sells at price $p_c(a)$. While power plant in a competitive market takes p_c as given, a power plant with market power will consider it a function of its abatement level, a. It costs $c_e(q_e)$ to produce q_e units of electricity. Each unit of electricity sells at price p_e.

The optimization problem of the power plant is to choose the output quantity and abatement that maximizes their profits

$$\max_{\{q_e,a\}\geq 0} \pi_e = p_e q_e - c(q_e) - \tau_E(\alpha q_e - a) + p_c(a)a - m(a)$$

where $\alpha \geq 0$ denotes the amount of CO_2 generated per unit of electricity output.

CO2-consumers: I consider extraction and manufacturing firms that operate in the vicinity of supply sources. The number of manufacturing firms is n_I. I assume firms are price-takers in their product markets and sell their output at a price $p_i > 0$. Manufacturing firms pay a per unit carbon tax $\tau_I \in \mathbb{R}$ for its net emissions of CO_2. Notice carbon taxes differ between power plants and manufacturing firms. In principle, this can reflect a carbon tax credit given to manufacturing firms to incentivize CO_2 utilization or sequestration [17]. I further assume $q_c(q_i) = \sigma q_i$ where $q_c(q_i)$ is the amount of CO_2 required to produce q_i units of industrial output, where σ is a measure of the productivity of carbon dioxide industrial processes. Manufacturing firms pay a price per unit of CO_2 equal to $p_u(q_i)$. While manufacturing firms in a competitive market take p_u as given, a manufacturing firm with market power will consider it a function of its demand for carbon, $q_c(q_i)$.

The objective of the manufacturing firms is to maximize their profits choosing over their production levels

$$\max_{q_i\geq 0} \pi_i = (p_i - \beta_i\tau_I)q_i - c_i(q_i) - p_u(q_i)q_c(q_i)$$

where the parameter $\beta > 0$ denotes the amount of CO_2 generated per unit of industry i's output.

Market Clearing: The CO_2 market clearing condition closes the model:

$$n_E a = n_I q\_c(q_I)$$

This condition connects the two sides of the market by equating CO_2 supply to CO_2 demand. Given considerable costs in shipping CO_2 to remote sites, the CO_2 market tends to be localized and its market structure will be crucially determined by the costs of transportation and the proximity of demand and supply firms. The equilibrium in CO_2 prices depends on the overall market structure which is characterized by the number of firms operating in each side of the market as sellers and buyers for CO_2. The number of firms n_E and n_I characterizes the nature of the market structure which is in turn determined by the transportation network. I start assuming there is no entry or exit into the CO_2 market but relax this assumption as an extension of the model. In a competitive market several firms act as price-takers in both sides in the CO_2 market and $p_c(a) = p_c = p_u = p_u(q_i)$. Another plausible case is a monopoly where many manufacturing firms play as competitive buyers for the limited supply of CO_2 so that $p_c(a) = p_u$. When there are only a few manufacturing firms and many CCS firms, the market can be characterized as a monopsony so that $p_c = p_u(q_i)$. In this case, all market power goes to the manufacturing firms because they become a competitive bottleneck vis-a-vis power plants that compete for limited demand for CO2.

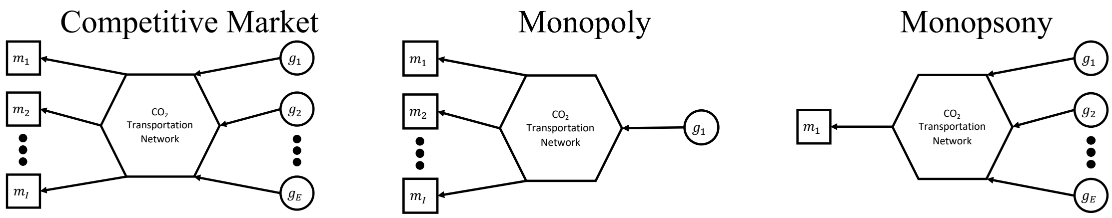

Figure 1: Different market structures resulting from limited transportation capacity.

With this framework in place, I plan to solve for the general equilibrium prices and quantities that determine the behavior of the market under different configurations. The questions I am expecting to answer are: How does a carbon tax interfere with the carbon dioxide market? How can we design a climate policy that encourages clean production while accounting for this interaction? What is the role of the network in determining economic outcomes?

2.1.2. Pipeline capacity expansion

This expansion introduces a network operator that decides whether to increase the flow capacity of the network. This introduces new frictions because the network operator can affect, via their decisions, the outcomes of the market. In this setting, the objective function of the network operator is to maximize profits by selecting the capacity of the network, K, that in turns determines how much CO_2 can flow through their system, $q_o(K)$. The operator incurs in costs $c_o(K)$ to maintain a network of capacity K. For simplicity, I assume there is no storage. The price paid by manufacturing firms to the network operator is $p_o(K)$ and the price paid to the power plants for their CO_2 is $p_{co}(K)$. The objective of the network operator is then to choose network capacity in order to maximize profits

$$\max_K \pi_o = p_o(K)q_o(K) - p_{co}(K)q_o(K) - c_o(K)$$

The market clearing condition is given by: $n_E a = n_I q_c(q_i) = q_o(K)$. Notice here that the prices paid to the power plants for their CO_2 is not the same as the price paid by the manufacturing firms, the markup being a function of the capacity of the system and the costs of maintain that capacity. With the introduction of the network operator, I consider three different market configurations: i.) The network operator is independent of the supply and demand of CO_2, ii.) power plants are vertically integrated with the network or iii.) manufacturing plants are vertically integrated with the network.

The objective of this expansion is to analyze the role of network capacity in determining the viability of carbon dioxide markets. Again, borrowing from the two-sided market literature [21], this expansion allows me to ask the question of how to manage an expansion in capacity when there are dual forces shaping the market as the platform of exchange expands. It also introduces interesting strategic behavior that could further explored using this framework.

2.1.3. Firm entry and exit into the carbon dioxide market

The initial setting corresponds to a fix number of firms in either side of the market. This model extension allows for power plants to pay a fixed costs to invest in CCS capacity, F_e, that allows them to capture CO_2. Similarly, I assume manufacturing firms need to retrofit their production process to use CO_2 as an input paying a fixed cost, F_i. I further assume firms in both sides of the market differ on their productivities, so that only a subset of firms in each side enters the CO_2 market. In this case, the market clearing condition is such that

$$n_E(F_e)a = n_I(F_i)q_c(q_i) = q_o(K)$$

The objective of this expansion to understand the role of carbon policy and market structure in creating a robust carbon dioxide market. High carbon taxes increase incentives for power plants to capture CO_2, but if those firms can pass those the costs onto their consumers, then high carbon taxes could result in fewer firms entering the demand side of the CO_2 market.

2.2. Dynamic Model

I extend the static framework to introduce important dynamic considerations such as scarcity in sources and sinks of CO_2 and market expansion via endogenous technological change that either expands the demand for CO_2 in different industrial uses or expands the supply by reducing the costs of building and operating carbon capture facilities.

2.2.1. Sources and sinks: Industrial CO_2, air and underground deposits utilization and storage.

The first limitation of the static approach is that it does not explicitly incorporate scarcity. In the context of CCUS, there are two important channels of scarcity that affect overall market performance. First, the amount of CO_2 captured is limited the amount of carbon dioxide produced by existing power plants. This flow of CO_2 can be supplemented by two stocks: extraction of natural underground CO_2 deposits and direct air capture. Second, the amount of CO_2 flow that can be absorbed by the market is limited by the number of manufacturing firms that can utilize carbon dioxide in their production process. Some CO2 can be injecting carbon dioxide in natural reservoirs, but those are scarce, are subject to spatial constraints, and could require different transportation infrastructure [25]. This extension allows me to ask question about the dynamic interplay between extraction and sequestration, the role of CCUS as a transitional technology for negative emissions like DAC, and optimal policy design.

2.2.2. Expanding the carbon dioxide market

In this section, I explore the endogenous evolution of the size of the market. The endogenous arrival of intermediate firms that can utilize carbon dioxide in their production function plus the economies of that results from investment in CCUS capacity, could lead to more robust carbon dioxide markets.

Learning by Doing in CCS: Expanding the supply side of the market: Firms can invest in reducing the costs of CCS. To keep this process tractable, I will assume the process of learning by doing decreases the cost of investing and operating CCS technologies as a function of cumulative investment [4]. Assuming firms are price takers, these costs reductions transfer directly to buyers thus increasing the number of firms that would find it beneficial to use carbon dioxide in their production processes.

CCUS Innovation: Expanding the demand side of the market: The model in section 2.1.3 is a reduced-form static version of a model where firms investment decisions create the conditions for market penetration. Here, I assume firms can engage in costly innovation to create products and processes that can make use of CO_2 as an input. I introduce an expanding varieties model where the number of products that can utilize CO_2 as an input increase as innovators allocate more resources to innovating activities.

The combination of these two processes, learning by doing and expanding variety, could results in a more robust CO_2 market. This dynamic extension allows me to tackle questions such as the optimal timing of carbon policy, the role of incentives in spurring innovation, and the determinants of the rate of growth of the carbon economy.

2.3. Climate Policy Model

In this section, I consider the role of carbon capture and utilization in the larger context of climate policy and as part of a portfolio of options that include traditional mitigation and carbon dioxide removal. I introduce the concepts developed in the previous section into the Dynamic Integrated Climate and Economy (DICE) model and carefully calibrate the model to explore how CCUS enters the conversation as one option within a larger set of that include emissions reductions, negative emissions (e.g., BECCS and Direct Air Capture), adaptation, and solar geoengineering [5,6,15].

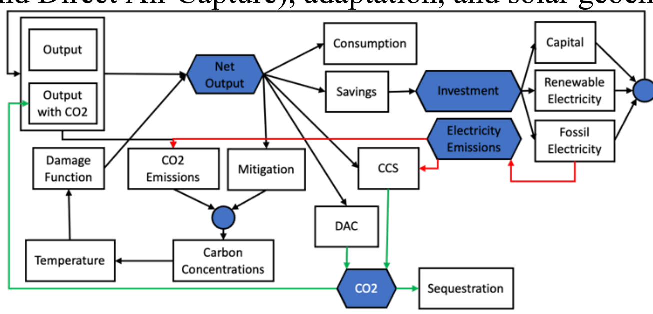

Figure 2: A schematic of the Dynamic and Policy models

The goal of this model is to provide a tool for policy makers and to ask questions about the role of CCUS in the transition to deep decarbonization. I am interested in exploring the role of CCUS in flattening the peak of greenhouse gas concentrations and as transitional tool to enable other forms of negative emissions. There are three important extensions to the DICE model that I will introduce to capture the nuances of CCUS in a larger portfolio of options. First, I will introduce an electricity system with two generation sources: clean and fossil [3,24]. The second extension introduces two sources of carbon dioxide, direct air capture and CCS. The third extension allows the CO2 to be injected in geological formation does reducing the emissions and concentrations of carbon in the atmosphere and, importantly, also introduces a sector that uses carbon dioxide in its production process. I will explore optimal policy design, but also second-best policies. In this regard, I consider regulators do not have the capacity to commit to a given carbon tax [2], and can change their behavior depending on, among other things, the cost of renewable sources, oil prices, technical costs and market expansion.

3. Scope and timeline

My goal is to present a comprehensive research agenda that can be developed as a sequence of tasks within the timeline of the current call for papers. My proposal is not commensurate with the stipend but with the 2.5 years duration of the project. The project I am proposing is admittedly too ambitious for one single paper. Although my intention is to write one comprehensive paper for the special issue, realistically, it is also possible that I will have to split the research into three papers: one paper for the static model, one paper for the dynamic model, and one paper for the climate policy model.

<u>Timeline:</u>

- Fall 2022: Static model set up and initial results (Section 2.1.1)
- Spring 2023: Capacity expansion (Section 2.1.2) and entry and exit (Section 2.1.3)
- Fall 2023: Dynamic model set up and sources and sinks (Section 2.2.1)
- Spring 2024: Complete paper draft including endogenous market expansion (Section 2.2.2)
- Fall 2024: Climate policy model (Section 2.3)

4. Conflict of Interests

I have no ties to the energy industry or any other potential conflicts that might bear on my proposed research.

5. References

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