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Carbon capture and renewable energy policies: Could policy harmonization be a puzzle piece to solve the electricity crisis?☆

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ABSTRACT

The electricity market crisis, driven by factors such as increased energy demand, rising fuel prices, aging infrastructure, and greenhouse gas emissions, requires a multifaceted approach including the strategic implementation of Carbon Capture and Storage (CCS) technologies, which despite high costs and potential adverse impact on renewable investments, can allow the use of fossil fuels to maintain grid stability, and simultaneously lower carbon footprint. Across the world, several nations are designing financial incentives and improving regulatory frameworks to reduce barriers to the deployment of CCS. However, it is not clearly understood whether and to what extent such policy support would affect the incentive to invest in renewable energy technologies. Moreover, it is unclear whether existing renewable subsidies would complement or counteract power generators' prospective investments in carbon capture retrofits in the presence of CCS subsidies. This study examines the rate of change in renewable energy generation with changes in CCS subsidies as well as the rate of change in the percent of carbon captured for storage with a change in renewable energy production subsidies (cross-impact of policies). The results, under the given model framework and assumptions, indicate that (1) renewable subsidies could lower the incentive to capture a larger share of carbon dioxide emissions for permanent storage, and (2) CCS subsidies could reduce the incentive to produce more renewable energy. These results highlight the need for policy makers to consider the potential trade-offs signaled by CCS policy support.

1. Introduction

Electricity markets are facing a crisis due to a combination of factors ranging from increase in energy demand relative to supply (e.g., due to weather conditions such as cold winters or hot summers), increase and volatility in fuel prices (e.g., due to geopolitical factors and import dependency) (Pourkhanali et al., 2024), aging or outdated electric infrastructure, and tackling greenhouse gas (GHG) emissions from fossil-based fuels (Pham et al., 2024). As a result, policymakers worldwide are grappling with these challenges and exploring ways to ensure energy security, affordability, and sustainability while making progress towards an energy transition. Addressing the electricity crisis in economies with ambitious energy transition goals requires a multifaceted approach that properly considers trade-offs among alternative strategies. On one hand, the shift from fossil-based to renewable power sources could affect grid stability due to the intermittent nature of renewable generation while on the other hand, continued reliance on fossil-based assets would slow down progress in the energy transition.

Carbon capture and storage (CCS) technologies are proposed as a potential puzzle piece to address the electricity market crisis, particularly in the context of transitioning to net-zero emissions. CCS has the potential to extend the lifespan of some fossil fuel plants to provide stable power supply, and at the same time allow for emissions reduction to contribute to overall decarbonization efforts. For example, in locations and at times when renewable energy sources are volatile and fluctuate, carbon capture-equipped power plants could provide the option to supply power and hence contribute to grid stability while contributing to reducing the overall carbon footprint of these facilities. CCS technologies can also remove carbon from the atmosphere to balance emissions that cannot be directly abated or avoided (International Energy Agency, 2021).

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However, it is important to note that while CCS could play a significant role in mitigating the electricity market crisis, it also presents critical challenges. For instance, the economic cost of CCS is currently very high (Davies et al., 2013; Fan et al., 2018; Fraga et al., 2024), and so are the social risks (d'Amore et al., 2018) and technical uncertainities (Huang et al., 2013, 2021). Additionally, the implementation of CCS technologies needs to be strategically planned and managed to ensure it complements other broader climate policies and effectively contributes to the energy transition. Thus, more studies are needed to evaluate potential trade-offs of promoting CCS, such as the impact on incentives to invest in renewable energy technologies (International Energy Agency, 2021; National Renewable Energy Laboratory, 2021).

CCS technologies enable electricity producers to manage carbon dioxide emissions, comply with regulatory requirements, and demonstrate corporate social responsibility. CCS policy incentives such as subsidies, tax credits, or direct support (e.g., R&D grants for developing energy-efficient carbon capture processes) are *specific* instruments expected to be the primary sources of monetization for adopting CCS technologies (Yang et al., 2019; Li et al., 2023). For example, in the US context, Section 45Q of the Inflation Reduction Act offers $85 in tax credit for each ton of carbon dioxide permanently stored. Canada has tax credits for investment in CCS equipment (e.g., 50% investment tax credit for CCS equipment). These financial incentives are expected to be instituted within a stable regulatory framework that reduce administrative burdens and challenges (e.g., monitoring, liabilities, permitting, etc.) to allow a cost-effective technology adoption. For instance, states such as Wyoming and Indiana are actively enacting legislation to shift long-term liabilities associated with carbon capture sites to the state to incentivize CCS investments (Waxman et al., 2021; Fikru, 2022).

Previous studies have evaluated the effect of different types of policy incentives on CCS adoption among power plants (Li et al., 2023; Gerlagh and Zwaan, 2006). Aune et al. (2022) use a game-theoretical approach to study the effect of CCS subsidies in promoting CCS adoption by comparing subsidies instituted on CCS technology developers versus subsidies instituted on technology adopters (e.g., coal-based power generators). The study shows that financial subsidies for technology developers work better in promoting CCS technology diffusion. Similarity, Nawrot and Walkowicz (2023) argue for the need to have broader policy incentives that support technological development, deployment, and operation to facilitate the use of CCS technologies to address net-zero goals. Krahé et al. (2013) argue for the need to have multiple policy incentives to support CCS development and correct market failures where policies should be adaptable and flexible to maturing technology as well as reduce uncertainties to encourage private investment. Azure et al. (2023) find that uncertainty in CCS subsidies could create greater variability in the profitability of CCS retrofits among US power generators. Similarly, Fikru (2022) shows that both a carrot (subsidy) and a stick (carbon tax) approach are needed to facilitate electricity decarbonization using a combination of cleaner production and carbon management technologies. Yang et al. (2019) compare different types of CCS subsidies encompassing the full-chain of CCS operations (e.g., initial investment subsidies for retrofitting plants, carbon capture and management subsidy, etc.). The study also considers an electricity tariff subsidy similar to renewable energy subsidies and shows that for certain levels of renewable subsidies, CCS projects will not be economically feasible highlighting the lack of synergy effect between CCS and renewable energy.

Despite the growing number of studies evaluating the impact of policy-induced financial incentives on decarbonization strategies among power plants (Azure et al., 2023; Chu et al., 2024; Chen et al., 2016), there are very limited economic frameworks used to comprehensively examine the potential impact of CCS subsidies on the incentive to produce cleaner energy from renewable sources (Fan et al., 2020). There is also a need to develop economic models to understand the mechanisms through which higher renewable subsidies could alter the incentive to invest in CCS as a carbon management strategy (*cross impact of policy*). This is because, in parallel to CCS policies, several nations have a wider range of other climate change policies seeking to incentivize large-scale renewable energy production (e.g., investment tax credits, production tax credits, etc.) and cut greenhouse gas (GHG) emissions (e.g., carbon pricing, carbon trading, emission standards, etc.).

Fig. 1 presents a ranking of countries with respect to two policies: (1) *specific* CCS policies most of which are in terms of subsidies, and (2) other *broader* environmental protection policies that seek to reduce GHG emissions. For example, in the US, power generators that capture carbon for permanent geological storage get a tax credit of $85 per ton of carbon and this is considered as a specific CCS policy incentive. Similarly, in the US, energy producers that use wind turbines get a 1.5 cents per kilowatt hour of production tax credit (PTC) while solar energy producers receive 22% investment tax credit (ITC) (Azure et al., 2023). These tax credits (PTC and ITC) are considered as renewable subsidies.

The figure illustrates that while some countries that are front-runners in designing policy support for CCS projects also rank higher in stricter environmental protection policies (e.g., Norway and Japan) (Global Carbon Capture and Storage Institute, 2021; Li et al., 2013), others may not necessarily rank among the top in terms of broader climate policies (e.g., USA, China, etc.) despite their leading status in CCS policies (see Appendix for additional illustration).[1] While some countries may find it feasible to adopt CCS policies in isolation to advance technology adoption, most others may already have policies in place to incentivize both cleaner production and carbon management. In the latter case, it is important for CCS subsidies complement (rather than contradict) the effect coming from other policies, such as carbon pricing, renewable energy incentives, and emissions regulations, to achieve overall emission reduction goals cost-effectively. This is because certain policy incentives that directly incentivize CCS could encourage carbon-intensive production at the expense of cleaner production. For example, if CCS subsidies are higher than renewable subsidies (e.g., per kilowatt hour), power plants may direct investments towards carbon capture retrofits in place of investing in renewable energy sources.

Despite the need to examine the strategic response of power generators to CCS versus renewable policy incentives, most studies so far focus on evaluating the impact of CCS policies on CCS investments (Yang et al., 2019, 2021) (e.g., in China, Li et al. (2023) evaluate the impact of carbon markets and subsidies on CCS retrofits; Aune et al. (2022) study upstream and downstream CCS subsidies, etc.). Given that CCS policies are relatively newer and more jurisdictions are expected to design new policy approaches to encourage net zero emissions via CCS, it is not clearly understood which combination of policy instruments provides a cost-effective path to achieve a net emissions energy system via both cleaner production (renewable) and carbon management (CCS) (Hong, 2022). This study fills the research gap by developing a model that captures the impact of CCS subsidies on renewable energy generation and the impact of renewable subsidies on using CCS technology for carbon management. While previous studies have individually explored the effects of CCS subsidies on CCS (Li et al., 2023; Aune et al., 2022; Colombe et al., 2023) or examined the influence of renewable subsidies on cleaner production (Gerlagh

[1] Global CCS Institute's CCS policy index measures a nation's policy environment in terms of directly supporting CCS technology deployment and other approaches that create opportunities for CCS. Most of the CCS policy support is in the form of subsidies, tax credits, direct support or R&D support. The OECD's globally comparable Environmental Policy Stringency index measures the extent to which environmental policies put an explicit or implicit price on activities that generate GHG emissions. The index covers a wide range of market and non-market based instruments that put a price on pollution (e.g., carbon trading, carbon tax, emission limits, subsides for renewable energy, etc.) (Kruse et al., 2022).

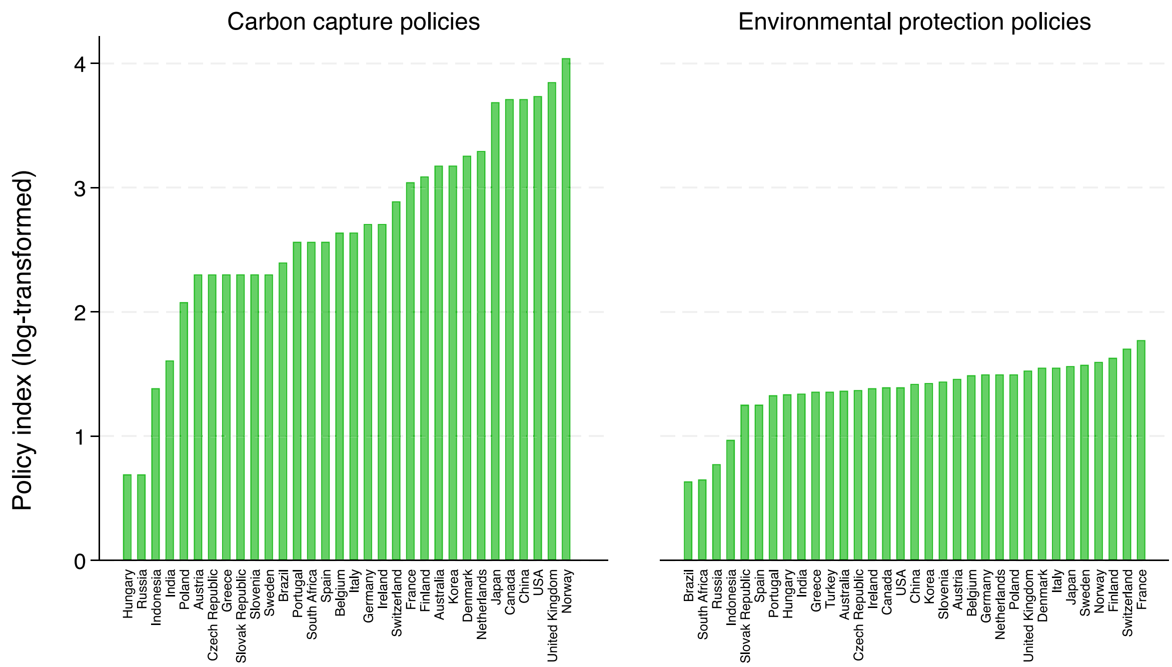

Fig. 1. Carbon capture policy incentives are measured by a score developed by the Global CCS Institute where a higher score represents generous policy support. Environmental protection policies are measured by an index developed by the OECD where a higher score indicates stringent climate policies. Both scores are log-transformed.

and Zwaan, 2006; Fikru and Canfield, 2022), this study takes a unique approach. The study focuses on theoretically modeling the *cross impacts*, investigating how CCS subsidies affect renewable or cleaner production and how renewable subsidies impact CCS investments. The theoretical modeling strategy also considers the impact of these policies on strategic firm responses (responses that maximize profit) instead of looking at only economically feasible outcomes under a given policy regime as was done in previous studies such as Yang et al. (2019), Sgouridis et al. (2019), and Azure et al. (2023). See Appendix for a discussion of insights from existing studies and the value added of the model presented in this paper compared to others that focus on techno-economic analysis (Ng et al., 2013; Owebor et al., 2022; Philbin and Hsueh-Ming Wang, 2019; Psarras et al., 2017; Sukor et al., 2020; Ye et al., 2019), uncertainty (Van der Spek et al., 2020; Zhu and Fan, 2011), and local environmental impacts (Waxman et al., 2023).

More specifically, this study presents a Cournot market of energy producers that can adopt carbon capture retrofits (to capture carbon dioxide for permanent geological storage) and cleaner energy technologies with profit maximization objectives. The model includes three policy instruments: CCS subsidies, renewable production subsidies, and carbon tax. Optimal energy production level and percent of carbon captured for storage are characterized to examine the impact of the three policy instruments on firm-level decision making. The study considers two major causes of the electricity market crisis in the context of an energy transition: the need to control carbon emissions and the importance of maintaining grid stability. As nations transition towards renewable energy sources, it is crucial to maintain grid stability to prevent disruptions in electricity supply. Therefore, the study's findings have significant implications for policymaking and investment decisions in the energy sector, which can ultimately help address the electricity crisis.

The rest of this paper is organized as follows: Section 2 presents the model and certain simplifying assumptions, Section 3 presents and discusses results obtained from the theoretical model, and Section 4 concludes with policy implications.

2. Model set-up and assumptions

This study differentiate CCS policies from other broader climate change policies that are designed to reduce greenhouse gas (GHG) emissions. The Section 45Q tax credit is an example of CCS subsidy. Other policies incentivizing deployment of CCS technologies include different types of direct financial support, tax incentives (e.g., property or income tax exemptions), cost recovery provisions, and investment tax credits (e.g., Canada has up to 50% investment tax credit for CCS equipment purchase). The Global CCS Institute has developed a policy indicator score (referred to as CCS policy) ranging from 0 to 100 to measure the extent to which countries provide direct financial support for CCS projects (e.g., US has a score of 49, Canada has a score of 41, and China has a score of 40) (Source: https://co2re.co/Policies). This study presents a case where a CCS subsidy is used as a proxy for financial policy incentives where firms that capture a ton of carbon dioxide are given a fixed amount of s dollars as a carbon capture and management subsidy if they permanently store the captured carbon dioxide. CCS subsidies are expected to create the direct incentive for installing carbon capture retrofits for the purpose of capturing carbon for permanent storage.

Broader climate change policies are primarily focused on reducing carbon emissions and facilitating environmental protection via cleaner energy productions. For example, the OECD provides an internationally comparable country-level index to measure the stringency of climate policies for each country. The index, referred to as the Environmental Policy Stringency or EPS ranges from zero for countries with lax climate policies to six for countries with the highest degree of climate policy stringency (Source: https://stats.oecd.org/Index.aspx?DataSetCode=EPS). As of 2020, France has the highest EPS score of 4.9 and Brazil has one of the lowest score of 0.9 (see Fig. 1). These climate policies put a direct or indirect price on carbon emissions and such effects are captured in the model by using a carbon tax t for each ton of carbon dioxide that ends up in the natural environment (Kruse et al., 2022). A carbon trading scheme with the price of carbon set to t could play a similar role. A renewable energy support is also modeled here in the form of production subsidies (represented by s_r) for each unit of energy produced using cleaner and greener sources. Policy instruments such as carbon tax and renewable production subsidies are expected to create the signal to transition from fossil to cleaner production technologies.

Studies show that climate policies such as carbon tax and renewable production subsidies affect cleaner energy production such as producing more renewable energy (e.g., Gerlagh and Zwaan, 2006) while CCS

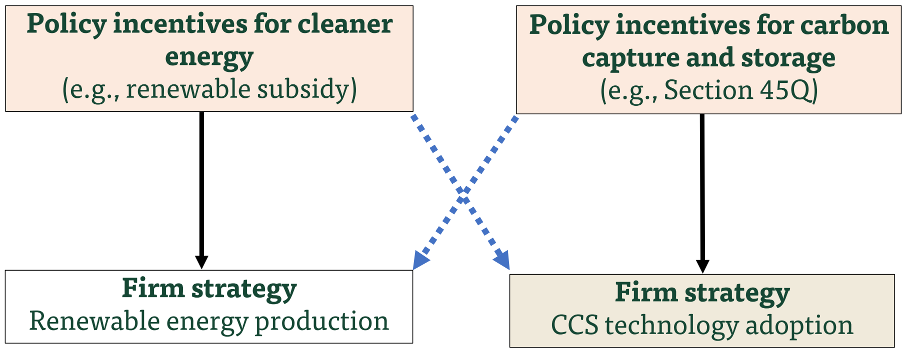

Fig. 2. This study examines the cross impact of policies: The impact of renewable subsidy on CCS and the impact of CCS subsidy on renewable generation.

policies create incentives to adopt carbon capture retrofits and CCS technologies (e.g., Yang et al., 2019). In the presence of both policies, this study examines the potential impact of renewable energy policies on altering carbon capture incentives as well as the potential impact of CCS subsidies on renewable energy generation. Fig. 2 presents the general conceptual framework presenting the two policies and their direct impact on firm strategies. The solid line represents effects established in the literature while the dashed lines are examined in this study.

2.1. Electricity producers and market demand

The model features a generic Cournot market where there are n number of power generators or firms such that each generator is denoted by $i = 1, 2, \ldots, n$. The model is built under several assumptions summarized as follows:

Assumption 2.1. (i) The market structure features n number of firms competing in a Cournot market, (ii) Firms produce two substitutable energy products, renewable and non-renewable, and energy demand is linear, (iii) Marginal cost of producing renewable energy is zero, (iv) Carbon transport and storage infrastructure (e.g., pipelines, reservoirs, etc.) are assumed to already exists.

Each generator produces electricity using renewable and non-renewable energy sources, represented by q_r and q_f respectively both measured in mega watt hours per period (mwh). Each generator also makes decision regarding the amount of carbon dioxide to capture via a carbon capture retrofit for permanent geological storage. The total megawatt hour (mwh) of electricity production per firm i is represented by $q_i = q_{f,i} + q_{r,i}$ (subscript r stands for renewable and f non-renewable or fossil source) such that $e_i = \sigma_i q_{f,i}$ is total carbon dioxide emissions and σ_i is each firm's carbon-intensity (e.g., carbon tons generated per mwh of fossil based generation). For example, power plants that rely on natural gas may have a lower carbon-intensity than coal-fired plants. Renewable energy is assumed to have close to zero carbon emissions.

Energy consumers view renewable and non-renewable energy as imperfect substitutes where the parameter γ measures the degree of product differentiation (Aune et al., 2022). $\gamma = 0$ holds if the two products are viewed as totally different, hence representing two different markets. Consequently, the inverse demand function for renewable and non-renewable energy is given below where P_f and P_r are the respective prices (Kaenzig et al., 2013; Knapp et al., 2020):

$$P_f = \alpha - \beta_f \sum (q_{f,i}) - \gamma \sum (q_{r,i}) \tag{1}$$

$$P_r = \alpha - \beta_r \sum (q_{r,i}) - \gamma \sum (q_{f,i}) \tag{2}$$

The parameter representing the reservation price for electricity is strictly positive, $\alpha > 0$ and the parameters β_r and β_f are also strictly positive. $\beta_f > \gamma$ and $\beta_r > \gamma$ capture the case where consumers value the variety of electricity options (renewable versus non-renewable). If $\beta_f = \gamma$ and $\beta_r = \gamma$ the two products are perfect substitutes. A representative firm (energy generator) sells cleaner electricity at a price P_r (Conte and Jacobsen, 2016) and non-renewable electricity at P_f. Studies such as Sundt and Rehdanz (2015) and Gustafson et al. (2019) show that the two products command different prices. For example, according to the US Environmental Protection Agency (2021) and the United States Energy.gov (2022), in the US market the average green price premium ($P_r - P_f > 0$) for renewable electricity is two to three cents per kWh (Gustafson et al., 2019; Fikru and Canfield, 2022). Although a linear electricity demand in Cournot markets is also modeled by Willems (2002), Yao et al. (2008), Milstein and Tishler (2015) and others, Eqs. (1) and (2) explicitly factor in how and to what extent consumers view renewable versus non-renewable energy as substitutes (Kowalska-Pyzalska, 2018).

Each firm receives a per unit subsidy for each mwh of electricity produced using renewable sources represented by s_r dollars per mwh of green electricity (e.g., Production Tax Credits or PTC) (Energy.gov, 2022). Thus, the total value of renewable production subsidy is represented by $s_r q_r$. Because of its carbon capture retrofit, a representative firm captures a percentage k of the total emissions, e, it generates, and this is transported elsewhere where it is permanently stored in geological formations. The firm gets a per unit subsidy (s) for each ton of carbon dioxide captured for storage (the CCS subsidy) where the value of total subsidy received is calculated as $sk\sigma q_f$. For example, in the US market, the Section 45Q tax credit provides up to \$85 per metric ton for carbon captured for geological storage (Waxman et al., 2021). Finally, the firm pays a carbon or emission tax of t for any units of carbon dioxide that ends up in the environment. The tax payment is given by $t(1-k)\sigma q_f$.

Each firm makes simultaneous decision on (1) energy production levels using renewable sources versus fossil fuels, and (2) abatement level regarding how much of the generated carbon dioxide to capture via the carbon capture retrofit and CCS technology. The representative firm is a multi-product producer with the objective of maximizing profits. The multi-product option together with product differentiation in an oligopoly market sets the model apart from existing models such as Fikru (2022) that use competitive market assumptions:

$$\pi_i(q_{f,i}, q_{r,i}, k_i) = P_f q_{f,i} + P_r q_{r,i} - C_i(q_{f,i}, q_{r,i}, k_i) + s_r q_{r,i} + s k_i \sigma q_{f,i} - t(1-k_i)\sigma q_{f,i} - F \tag{3}$$

Each generator's profit, π_i, is defined as revenue from the two electricity products less the power generator's costs ($C_i(.)$ represents generator's production and carbon management cost) and adding cash inflows due to subsidies less cash outflows due to tax. The term F stands for fixed costs hence representing short-run decisions.

2.2. Cost function properties

Each firm's cost function $C_i(.)$ fulfills the usual cost properties (that is, convex and differentiable) and captures both the cost of *energy production* and cost of *carbon management*. First, the generator incurs cost of producing energy where the marginal cost of producing renewable energy is assumed to be zero. For example, Acemoglu et al. (2017) present a linear demand for energy production where the marginal cost of renewable generation is assumed to be zero. The cost function also incorporates the energy penalty cost imposed by the carbon capture retrofit on power generation (Fikru, 2022). This means the marginal cost of producing non-renewable energy from the portion of power plant where the carbon capture equipment is fitted, increases as the percent of carbon captured increases (Goto et al., 2013; Hammond et al., 2011).

The cost function also includes the cost of transporting and storing carbon because firms transport and store all the captured carbon in geological formations. To maintain model tractability, a simplified cost function is considered where (dropping i subscripts for brevity), $C(q_f, q_r, k) = cq_f + gq_f q_r + \rho q_f k + \theta k^2/2 + dk\sigma q_f$, given $c, g, \rho, \theta, d \geq 0$. The first term represents the cost of operating the fossil-based power plant, the second represents the ramping costs and the cost incurred when integrating renewable and non-renewable assets (e.g., generator needs to increase fossil based production while renewable sources go down or are intermittent) (Hirth et al., 2015; Horowitz et al., 2018), and the third term represents the energy penalty cost (e.g., higher k imposes additional cost of production) (Akbilgic et al., 2015; Budinis et al., 2018a,b; Fikru, 2022; House et al., 2009). The fourth term represents the carbon capture cost, and the last term indicates the cost of carbon transportation and storage. The generator captures $k\sigma q_f$ tons of carbon dioxide per period so transportation and storage costs depend on this level. The cost parameter $d > 0$ holds for a CCS regime where generators incur cost of carbon transportation and permanent storage.

Assumption 2.2. The following properties hold for $C_i(\cdot)\ \forall i$ (subscripts denote partial derivatives): (i) Production cost implies $C_{q_f} > 0$, $C_{q_r} \geq 0$, and $C_{q_f q_r} = g \geq 0$, (ii) Energy penalty cost implies, $C_{q_f k} = \rho + d\sigma > 0$, (iii) Carbon capture cost follows $C_k > 0, C_{kk} = \theta > 0$.

The intuition behind these follows: (i) C_{q_r} is the marginal cost of producing energy which is fully composed of the cost of integrating renewable into fossil-based assets (Yao et al., 2008) (e.g., for example, there is no energy storage system to store any excess renewable energy so the fossil generation needs to switch off during renewable peak hours). Since electricity produced from renewable sources is variable, intermittent, and less certain, firms incur higher additional costs as they integrate more renewable generation into their production plants. For example, power plants need to ramp up production from fossil based plants as renewable production comes down and vice versa, (ii) imply that firms incur energy penalty costs with a carbon capture retrofit which are higher when the level of fossil-based electricity are higher. For instance, Jenni et al. (2013) define the energy penalty cost as the decrease in output per unit of input as a result of a carbon capture retrofit. In addition, this cost component is affected by the cost of transporting and storing captured carbon dioxide, and (iii) marginal carbon capture cost is positive and increasing in the percentage of captured carbon.

Power generators or firms compete in a Cournot-Nash fashion by choosing simultaneously production levels (q_r, q_f) and the percent of carbon captured (k) for given policy parameters, and given the CCS technology.

2.3. Profit maximization conditions

The profit maximization problem gives the following three first order conditions:

$$\frac{\partial \pi_i(q_{f,i}, q_{r,i}, k_i)}{\partial q_{f,i}} = P_f + q_{f,i}\frac{dP_f}{dq_{f,i}} + q_{r,i}\frac{dP_r}{dq_{f,i}} - \frac{dC_i(.)}{dq_{f,i}} + sk_i\sigma - t(1-k_i)\sigma = 0 \quad (4)$$

$$\frac{\partial \pi(q_{f,i}, q_{r,i}, k_i)}{\partial q_{r,i}} = q_{f,i}\frac{dP_f}{dq_{r,i}} + P_r + q_{r,i}\frac{dP_r}{dq_{r,i}} - \frac{dC_i(.)}{dq_{r,i}} + s_r = 0 \quad (5)$$

$$\frac{\partial \pi(q_{f,i}, q_{r,i}, k_i)}{\partial k_i} = -\frac{dC_i(.)}{dk_i} + s\sigma q_{f,i} + t\sigma q_{f,i} = 0 \quad (6)$$

Eqs. (4) and (5) imply that the generator makes production decisions by comparing marginal costs to marginal benefits. The marginal benefit of energy generation includes the price of electricity and subsidy for cleaner energy production. The marginal cost consists of production and tax payment costs. The equations also illustrate the importance of the extent of product differentiation ($dP_r/dq_{f,i} = dP_f/dq_{r,i} = \gamma$) in each firm's decision making and market power.

Eq. (6) implies that the firm will increase k if the marginal benefits from the carbon capture retrofit (saving carbon tax payments and earning CCS subsidy) exceeds the marginal cost of capture. The model is solved by assuming symmetry across firms and hence one can ignore the i subscript while characterizing equilibrium values.

To make the model more tractable and focus on production and carbon abatement parameters, assume $\beta_f = \beta_r = \beta > \gamma$ without loss of generality. This assumption implies that any green price premiums ($P_r - P_f > 0$) are caused by differences in production levels where the volume of non-renewable energy exceeds renewable energy. This is consistent with real world markets where close to 60% of electricity generation comes from fossil based power plants (United States Environmental Protection Agency, 2022; United States Energy Information Administration, 2020). More formally the assumption leads to $q_f - q_r > 0$, if $(P_r - P_f)/n(\beta - \gamma) > 0$. If there is no product differentiation, the two prices will be valued the same (identical products), that is, if $\beta = \gamma$ then $P_r = P_f$ illustrating the impact of consumers' view on electricity pricing.

The objective of this study is to examine the cross impact of policies as presented by the dashed arrows of Fig. 2. Using optimal solutions from Eqs. (4) to (6), comparative statics is used to examine the cross impacts of policies. That is, the impact of CCS subsidy on renewable energy generation is characterized by using dq_r/ds, and the impact of renewable production subsidy on the percent of carbon captured by using dk/ds_r. Results of the comparative statics exercise are presented in Section 3. The results are interpreted as the strategic and optimal response of firms for changes in each given policy.

3. Results and discussions

3.1. Impact of policies on firm equilibrium values

Solving the first order conditions given in Eqs. (4) to (6) with symmetry gives the following three equations in three unknowns (q_f, q_r, k) where second order conditions ensure that profit is maximized:

$$\alpha - c - t\sigma - q_f\beta(n+1) - q_r[\gamma(n+1) + g] + k[\sigma(s+t-d) - \rho] = 0 \quad (7)$$

$$\alpha + s_r - q_f[\gamma(n+1) + g] - q_r(n+1)\beta = 0 \quad (8)$$

$$q_f[\sigma(s+t-d) - \rho] - \theta k = 0 \quad (9)$$

Eqs. (7) and (8) imply that increasing non-renewable production when renewable production declines, and reducing non-renewable production when renewable production increases, $dq_f/dq_r < 0$, is consistent with profit-maximization goals. This rate of change depends on two factors: product differentiation (the two products are not different but not perfectly substitutable) and the cost of integrating renewable production into a power plant (g).

Eq. (9) shows that the firm will increase the percent of carbon captured, k, when θ and ρ decline (cost increasing parameters), and when the CCS subsidy (s) and tax rate increases (cost reduction effect due to subsidies received or tax payment saved due to carbon capture).

Eqs. (7) and (9) also suggest that, at equilibrium, a higher level of fossil based generation is associated with a higher percent of carbon captured as long as $s + t - d > \rho/\sigma$. This condition implies that subsidy and tax savings benefit of carbon capture exceed costs (energy penalty, carbon transport and storage cost). This could facilitate decarbonization efforts when size of fossil-based generation increases. In other words, as the generator increases non-renewable production, it will generate more emissions, and then capture a greater portion of the generated carbon emissions for permanent storage. This holds as long as the CCS subsidy and tax payment savings benefit of carbon capture are sufficiently higher than the sum of the energy penalty cost of the carbon capture retrofit and the cost of carbon management (transport and store).

The closed form solutions are solved under a symmetric equilibrium as follows where $*$ represents equilibrium outcomes:

$$q_f^* = \frac{\theta[\alpha - \eta(\alpha + s_r) - c - t\sigma]}{\theta\beta(n+1)(1-\eta^2) - (s\sigma + t\sigma - d\sigma - \rho)^2} \tag{10}$$

$$q_r^* = \frac{\alpha + s_r}{\beta(n+1)} - \frac{\eta\theta[\alpha - \eta(\alpha + s_r) - c - t\sigma]}{\theta\beta(n+1)(1-\eta^2) - (s\sigma + t\sigma - d\sigma - \rho)^2} \tag{11}$$

$$k^* = \frac{[s\sigma + t\sigma - d\sigma - \rho][\alpha - \eta(\alpha + s_r) - c - t\sigma]}{\theta\beta(n+1)(1-\eta^2) - (s\sigma + t\sigma - d\sigma - \rho)^2} \tag{12}$$

where $\eta = \frac{\gamma(n+1)+g}{\beta(n+1)} > 0$ and $1-\eta^2 > 0$ as long as $(n+1)(\beta-\gamma) > g$. The parameter η captures the rate of strategic substitutability between renewable and non-renewable production which in turn depends on the extent of product differentiation and asset integration cost (g). The model assumes non-negativity constraints are met for production levels where $q_f^*, q_r^* > 0$, and $0 \le k^* \le 1$. Such constraints imply that the two products are not perfect substitutes and that $\beta > \gamma$ and so the analysis holds within this constraint.

The model predicts that renewable production subsidies incentivize firms to produce more renewable energy and less non-renewable energy as follows $dq_f/ds_r < 0$, $dq_r/ds_r > 0$. This is generally consistent with previous studies (Keohane and Olmstead, 2016; Malik et al., 2019; Zhang et al., 2022). In addition, the model suggests that renewable production subsidy (s_r) reduces the percent of carbon captured while CCS subsidy increases it where $dk/ds_r < 0$ and $dk/ds > 0$. The CCS subsidy incentivizes firms to produce more non-renewable and less renewable energy, $dq_f/ds > 0$, $dq_r/ds < 0$.

These latter results shed light on the importance of aligning CCS policies with existing climate policy frameworks that incentivize cleaner production; and understanding trade-offs, if any. For example, policy makers need to examine whether and to what extent CCS policies, in particular subsidies or tax credits, incentivize carbon management at the expense of renewable energy production. Given that CCS technologies are relatively newer, jurisdictions are designing several financial incentives to encourage the private sector to adopt these technologies. Furthermore, nations are adjusting regulatory frameworks to enable an infrastructure conductive for large-scale deployment of CCS technologies.

When new policy frameworks are proposed to encourage CCS technology development as well as their widespread adoption commanding a financial return, they should be designed and implemented in harmony with existing efforts to address electricity market crisis related to carbon emissions and grid stability. This is crucial because decarbonization goals are best achieved by adopting multiple or *do both* strategies (CCS and renewable production) than competing strategies (CCS or renewable production). As a result, policy incentives should signal the *do both* strategy rather than creating trade-offs to choose from. For example, under the given assumptions, the model highlights that a renewable production subsidy (s_r) provides the incentive to lower the percent of carbon captured (k) and increase greener electricity production (q_r) (this may have implications for grid stability); while a subsidy targeting CCS (s) encourages carbon management at the expense of cleaner production (e.g., potentially slowing down energy transition progress).

More formally the rate at which renewable production subsidy affects CCS and the rate at which CCS subsidy affects renewable production both depend on the parameter η which captures the rate of strategic substitutability between renewable and non-renewable energy (from the firm's point view) which in turn depends on how consumers view the two products as well as the cost of integrating renewable with non-renewable assets. For example, suppose $g = 0$ and $\gamma = 0$ represents a hypothetical scenario with no integration cost and completely different products. This scenario results in $\eta = 0$ and $dk^*/ds_r = dq_r/ds = 0$ (Fikru, 2022).

The comparative static results are more formally presented as follows:

$$\frac{dk^*}{ds_r} = \frac{-\epsilon\eta}{\theta\beta(n+1)(1-\eta^2) - \epsilon^2} < 0 \tag{13}$$

$$\frac{dq_r^*}{ds} = \frac{-2\epsilon\eta\sigma q_f}{\theta\beta(n+1)(1-\eta^2) - \epsilon^2} < 0 \tag{14}$$

where $\epsilon = \sigma(s + t - d) - \rho > 0$ to ensure a non-corner solution.

The impact of the carbon tax on production levels and percent of carbon captured are calculated as follows:

$$\frac{dq_f^*}{dt} = \frac{\sigma(2k-1)}{\theta\beta(n+1)(1-\eta^2) - \epsilon^2} \tag{15}$$

$$\frac{dq_r^*}{dt} = \frac{-\eta\sigma(2k-1)}{\theta\beta(n+1)(1-\eta^2) - \epsilon^2} \tag{16}$$

$$\frac{dk^*}{dt} = \frac{\epsilon\sigma(2k-1)}{\theta^2\beta(n+1)(1-\eta^2) - \epsilon^2\theta} + \frac{q_f\sigma}{\theta} \tag{17}$$

A higher carbon tax increases q_f as long as $k > 0.5$. This means for a sufficiently high percent of carbon captured (e.g., high carbon capture capacity retrofit), a higher emission tax encourages the production of non-renewable energy. This is due to a combination of two effects, (1) because of the strategic complementary relationship between k and q_f, for a high t firms will produce more non-renewable energy and capture a higher percentage, and (2) firms will get higher tax savings from a higher percent of carbon capture. In this scenario (i.e., $k > 0.5$), a higher tax reduces renewable production. Overall, if carbon capture retrofits are large enough, firms will increase q_f in response to an increasing tax while reducing reliance on renewable generation. In addition, $dk/dt > 0$ holds for the range $k > 0.5$ (sufficient condition).

On the other hand if $k < 0.5$, then $dq_f/dt < 0$, $dq_r/dt > 0$ holds where a higher tax penalizes non-renewable production because of a small tax savings effect from a lower k. The tax incentivizes renewable production. In this scenario, there are two opposing effects of tax on k : on one hand since q_f is declining with tax, the firm can afford to capture a higher percent of a now lower emissions so k increases, but on the other hand because of the strategic complement relationship between non-renewable production and carbon capture a lower q_f induces a lower k. The net effect is that $dk/dt > 0$ holds for all positive output levels as long as k is not too small (e.g., not close to zero). This result suggests that the relationship between tax and production/abatement decisions are non-linear.

3.2. Summary of findings and discussions

The theoretical results of this study are summarized in Table 1. Under the given model assumptions, (1) there is a positive relation between fossil based generation q_f and CCS policy, s, (2) there is a negative relationship between renewable generation q_r and CCS policy, s, highlighting the need to design CCS policies consistent with broader decarbonization goals so as not to impose a trade-off on firm's decision, (3) there is a positive relationship between s and k, (4) the impact of carbon tax on renewable and non-renewable production depends on the level of k, (5) higher t increases k, and (6) renewable production subsidies reduce fossil based generation and percent of carbon captured, also highlighting the need to align policy goals so as to reduce or eliminate existing trade offs imposed by existing policy approaches.

These results suggest that, (1) CCS subsidies could potentially lower the incentive for renewable energy production by providing signal for a strategic increase in non-renewable energy to allow for a larger volume of carbon emissions to be captured to benefit from CCS subsidies and carbon tax payment savings, (2) subsidies for renewable energy production could reduce the incentive to install carbon capture retrofits there by potentially creating unintended barrier to a *'do both'* approach

Table 1
Summary of analytical results: Direct and cross impact of policies.

Policy instruments	Non-renewable generation (q_f)	Renewable generation (q_r)	Percent of carbon captured (k)
Production subsidy (s_r)	Decrease	Increase	Decrease
Carbon capture subsidy (s)	Increase	Decrease	Increase
Carbon tax (t)	Increase if $k > 0.5$	Decrease if $k > 0.5$	Increase

to achieve deep decarbonization goals, and (3) there is a non-linear impact of carbon tax on electricity production where power generators with a higher CCS capacity are likely to increase fossil-based energy production at the expense of renewable production.

The implications of these results can be compared and contrasted with recent studies. For instance, when a cap-and-trade regulation is present, Amiri-Pebdani et al. (2023) find that both a CCS investment subsidy and a feed in tariff could improve the profitability of CCS applications but the investment subsidy is more cost-effective. Fikru (2022) finds that in competitive electricity markets with no product differentiation, CCS subsidies encourage carbon capture but would not alter the percent of energy produced using cleaner sources. These results are closer to Yang et al. (2019) who find that CCS may not be economically viable for a certain range of renewable subsidies.

Overall, the analytical results presented in this study establish the direction of the cross impact of policies where higher CCS subsidy lowers a firm's renewable generation and higher renewable subsidy lowers a firm's incentives to capture carbon. These results suggest that CCS policies alter market incentives and so should be carefully designed in harmony with other climate change policies to achieve objectives related to solving the electricity market crisis. The findings of this study also provide insight for policymakers in designing effective policies to reduce GHG emissions and accelerate the transition to sustainable energy systems.

The findings of this study have several implications for using CCS as a puzzle piece to address the electricity market crisis caused by increases in electricity demand, GHG emissions, and grid stability. As nations continue with ambitious energy transition goals, a careful policy design and alignment, supporting technological advancements, and shifts in consumption patterns are needed to address challenges in the electricity market. First, to mitigate the electricity market crisis, CCS policies need to be carefully designed to avoid undermining renewable energy investments. Policymakers should create balanced incentives that encourage both CCS and renewable energy without creating a bias towards fossil fuels. Encouraging a combination of CCS and renewable energy solutions can help diversify the energy mix, reduce emissions, and enhance energy security. Second, in addition to subsidizing policy incentives (carrot approach), implementing a carbon tax (as a stick approach) that appropriately prices carbon emissions could supports both CCS and renewable energy and provide a more balanced price signal for net-zero emissions. For example, carbon tax could help reduce overall emissions and achieve environmental quality without favoring one technology over another.

4. Conclusions and policy implications

This study examines the impact of carbon capture and storage (CCS) policies and broader climate change policies within the context of electricity production, contributing to the discussion on how CCS policies intersect with other climate-related incentives. The study models electricity producers driven by profit maximization goals, where firms consider carbon capture retrofits and cleaner energy technologies, in the presence of various policy instruments such as abatement subsidies and emissions taxes. The optimal market values for electricity production and carbon capture percentages are characterized and the impact of policies on firm-level decisions is examined. In particular, the study examines cross impact of policies, that is, the impact of CCS subsidies on renewable generation and the impact of renewable subsidies on capturing carbon for final storage.

The findings highlight several critical aspects important for the design and implementation of decarbonization policies in the presence of electricity market crisis. Firstly, under the given model framework and assumptions, CCS subsidies could unintentionally reduce the incentive for renewable energy production. This occurs as some electricity producers strategically increase non-renewable energy output to capture more carbon emissions, benefiting from both CCS subsidies and carbon tax payment savings. Thus, a potential trade-off could exist between promoting CCS and renewable energy technologies. Secondly, under the given model framework and assumptions, subsidies for renewable energy production could hinder the adoption of carbon capture retrofits, potentially creating barriers to a comprehensive decarbonization approach. Policymakers should carefully weigh the interplay between these two sets of incentives to encourage both cleaner production and effective carbon management. Policymakers should also effectively balance incentives for CCS and renewable energy to circumvent the potential trade-offs highlighted in this study.

For example, there could be room to design other types of policy instruments that incentivize a *do-both* or *bundle* investment strategy. In particular, policies can offer subsidies based on the net reduction in carbon emissions achieved by a facility, considering contributions from both renewable energy and carbon capture. This ensures that incentives align with the goal of comprehensive decarbonization. Policy makers could also create subsidy schemes that reward electricity producers for adopting both carbon capture technologies and increasing renewable energy output either simultaneously or sequentially. Additionally, this study finds that the impact of a carbon tax on electricity production is potentially non-linear suggesting the difficulty in the design of tax rates that provide the same signal for all types of firms. Power generators with a higher carbon capture capacity could be more likely to increase fossil-based energy production at the expense of renewable when higher carbon taxes are imposed. This highlights that carbon tax policies could significantly alter market dynamics and should be designed considering their impact on green technologies adoption. In some instances, carbon taxes together with other subsidies could provide both the carrot and stick needed for deep electricity decarbonization.

The implications of this study for policy and future research are multifaceted and hold immense significance in the context of climate change mitigation and the transition to sustainable energy systems. On one hand, integrating policy instruments is a crucial consideration for policymakers. An integrated policy approach, aligning carbon capture subsidies with broader climate policies like carbon pricing and renewable energy incentives, could stand out as a promising strategy. Policymakers must carefully assess potential trade-offs and synergies between a variety of policy instruments. Striving for a harmonious blend that encourages both cleaner production and effective carbon management is key to expediting the transition towards low-carbon energy systems. However, balancing dual incentives and supporting both strategies (cleaner production and carbon management) could have significant financial implications (e.g., higher need for public funds) which increases the overall cost of decarbonization. In addition, designing novel policies signaling a dual investment approach could have unintended consequences in the energy market. Furthermore, relying on only subsidies might not be a sustainable long-term strategy for either CCS or renewable energy technologies. There is a need to consider how market forces can be leveraged to make these technologies economically viable without long-term reliance on government support. More research is needed to address these challenges.

While this paper presents an analytical framework to examine the cross impact of policies, future studies can use the proposed model to simulate numerical results based on real-world data. Simulations can be used to estimate the strength of the impact of policies on firm decision variables. Another limitation of this study is the use of model assumptions that may not generalize or hold universally. For example, we assume a generic linear market demand while wholesale/retail electricity markets may not necessarily have a linear demand. Furthermore, not all electricity markets may have the type of market competition modeled in this work (i.e., Cournot market), and not all markets may face the given policy instruments. In addition, the model assumes that all other factors are held constant. For instance, when market dynamics change or when the cost of switching to renewable increases or when regional policy changes, the predicted cross impact of policies may not hold. Future studies can relax some of the model assumptions regarding the type of market competition, type of cost functions, type of energy demand function, etc. With different functional forms, results may change and not generalize.

Future research can also extend the framework provided in this study in other dimensions. Future studies could further investigate how well the comparative static results hold in different market structure and regulatory regimes. For instance, model implications could change in competitive markets and in markets regulated for electricity prices. In addition, regional variation in policy effectiveness would require a careful examination because different regions may face unique challenges and opportunities in adopting carbon capture and renewable energy technologies. Regional analyses can yield tailored policy insights to address specific circumstances. As CCS technological advancements evolve, research should assess how emerging innovations influence policy effectiveness and market dynamics. Evaluating the cost-effectiveness and scalability of these technologies could further inform policy making. Finally, it is important to have more comprehensive studies examining often understudied factors such as the role of political economy and evolving public attitudes, in shaping policy as well as technology deployment

CRediT authorship contribution statement

Mahelet G. Fikru: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fateh Belaïd:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation, Conceptualization. **Hongyan Ma:** Writing – review & editing, Writing – original draft, Validation, Resources, Conceptualization.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107753.

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