

**Can CCfD be an efficient low-carbon hydrogen innovation support instrument to meet the Paris Agreement commitments?**

**Student**: Damien Vincent

**Supervisor**: Lela Melon

**JEL codes**: K32, O31, Q55

I hereby declare and confirm that this thesis is entirely the result of my own work except where otherwise indicated. I acknowledge the supervision and guidance I have received from Lela Melon. This thesis is not used as part of any other examination and has not yet been published.

10/08/2022

Damien Vincent



**Abstract**: To meet PA objectives, counter the effects of the Covid crisis and the Ukraine war, the European Commission strengthened its climate ambitions through stimulus packages and legislative proposals. It announced that CCfD would be implemented within the current EU-ETS reform to support innovation in the low-carbon hydrogen sector. Being perceived as a transformative solution, the related technologies are however not mature yet and are inefficient. Besides, the EU-ETS regulatory framework suffered from design deficiencies altering its functioning over the first decade of its implementation. EU-ETS and CCfD would interact, the latter being based on the carbon price. Due to this, CCfD insurance nature and the integration of the geopolitical risk in the EU’s climate policy, this work identifies some risks. They refer to both public governance and public budget, notably a potential “self-imposed contractual capture” that could lead to immobilism in climate policy. To solve contradictory injunctions of the institutional/instrumental setup on one side and energy use on the other side, strengthening the EU-ETS and developing an energy sufficiency planification are proposed instead of CCfD.

**Keywords**: CCfD, Environmental Law, EU ETS, Paris Agreement, Hydrogen

**Table of Contents**

Acronyms list 6

List of figures, tables, and boxes 8

Introduction 9

Section 1: Theoretical framework 12

1.1. The microeconomics grounds of ETS 12

1.2. Economic theories of regulation and the private interest theory 15

Section 2: A source of important GHGE facing technological and economic

 uncertainties regarding its decarbonization potential 17

2.1. Current and expected hydrogen production methods 17

2.2. Current and expected hydrogen usages 19

2.3 LCH technologies are environmentally and economically inefficient 21

Section 3: EU-ETS, a regulation under the influence which began to operate properly

 recently 27

3.1 EU-ETS design deficiencies 27

 3.1.1 An initial scope definition under influence 28

 3.1.2 Governance flaws in the first EU-ETS phases 29

3.2 EUA price formation, evolutions, and predictability 30

 3.2.1 Endogenous factors 30

 3.2.2 Exogenous factors 32

3.3 Dynamic and environmental efficiency results 34

 3.3.1 Induced innovation and competitive process 34

 3.3.2 Environmental Efficiency 35

Section 4: CCfD to boost LCH in Europe, an efficient instrument? 38

4.1 An attractive instrument to reinforce projects’ financial viability 39

4.2 An unbalanced risk allocation 41

4.3 Institutional risks related to the technology 43

4.4 Anticompetitive effects 45

4.5 Correctly Pricing the Carbon to Evaluate CCfD Opportunity 46

Section 5: Discussion 49

5.1 LCH: a choice based on economic strategic behavior rather than

environmental efficiency? 49

5.2 CCfD: a misled and counter-productive instrument 51

 5.2.1 CCFD as an uncertain budgetary commitment and policy

 incoherence 51

 5.2.2 A regulation puzzle, potential source of a third type of regulatory

 capture? 53

5.3 Alternative policies 55

 5.3.1 The carbon price as an alternative? 55

 5.3.2 Energy and climate change understanding for an immediate

 environmental response: energy sufficiency planification 57

Conclusion 60

Bibliography 61

**Acronyms List**

CBAM: Carbon Border Adjustment Mechanism

CCfD: Carbon Contracts for Difference

CCS: Carbon Capture and Storage

CCUS: Carbon Capture Utilization and Storage

CFMP: Climate Friendly Materials Platform

CO2: Carbon Dioxide

CO2-eq: CO2 equivalent

DERA: German for *Deutsche Rohstoffagentur*, Mineral Resources Agency from the Federal Institute for Geosciences and Natural Resources (*Bundesanstalt für Geowissenschaften und* *Rohstoffe* - BGR)

EBRD: European Bank for Reconstruction and Development

EC: European Commission

EEA: European Environmental Agency

EPC: European Parliament and Council of the European Union

ETS: Emission Trading Scheme

EU: European Union

EUA: European Union Allowances

EU-ETS: European Union Emission Trading Scheme

GDP: Gross Domestic Product

GHG: Greenhouse Gas

GHGE: Greenhouse Gas Emissions

Gt: Gigatons

IEA: International Energy Agency

IF: Innovation Fund

IO: International Organization

IPCC: Intergovernmental Panel on Climate Change

IPE: International Political Economy

L&E: Law and Economics

LCH: Low-Carbon Hydrogen

LOHC: Liquid Organic Hydrogen Carriers

MAC: Marginal Abatement Costs

MS: Member States

MSR: Market Stability Reserve

Mt: Million Tons

MW: Mega Watts

N2O: Nitrous Oxide

OECD: Organization for Economic Co-operation and Development

OoM: Order of Magnitude

PA: Paris Agreement

PCT: Public Choice Theory

PFC: Perfluorocarbon

R&D: Research and Development

SMR: Steam Methane Reforming

TC: Thermochemical conversion

tCO2/year: Tons of Carbon Dioxide per Year

TWh: Tetra Watts per Hour

UNECE: United Nations Economic Commission for Europe

UNPE: United Nations Environment Program

WTO: World Trade Organization

**List of figures, tables and boxes**

Figure 1: Cost-effectiveness of emissions trading 14

Figure 2: Global dedicated hydrogen production 19

Figure 3: Net energy generation in the EU-27 in 2018 24

Figure 4: EU-ETS Price between 2005 and 2021 30

Figure 5: Overall IF program impact by sector 38

Figure 6: CCfD strike price and payments representation 39

Figure 7: Breakeven cost estimates of very low-carbon cement, primary steel and

 primary aluminum technologies 47

**Introduction**

GHGE result in extensive economic costs, from one to seven years of global GDP by 2100 (Wei et al., 2020) due to physical and transition risks, and risk transmission channels climate change implies (Köberle et al., 2021). In 2019, the EU represented the third largest emitter globally (EC, 2019a). To avoid triggering positive climate feedback, reaching tipping points (see IPCC, 2021 for definitions), and limiting undesirable consequences, the PA was concluded in 2015. It aims at strengthening States Parties’ actions to hold "the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” (UN, 2015). Under this internationally binding legal agreement, carbon neutrality from anthropogenic sources should be reached in the second half of the 21st century.

Simultaneously, the COVID-19 pandemic crisis has led to a historic recession, with the EU economy contracting by 6.3% in 2020 (OECD, 2021) having a negligible effect on long-term climate trends (Forster et al., 2020). In August 2021, the IPCC declared that “without immediate and deep emission reductions across all sectors, limiting global warming to 1.5°C is beyond reach." (IPCC, 2022b) Thus, the need to revive economic activity has been combined with climate objectives in recovery plans presented at both the national (e.g., *France Relance*) and European levels (e.g., NextGeneration EU). Further, reinforcing its Green New Deal ambitions, the EC has proposed cutting the EU’s GHGE by 55% by 2030 and achieve carbon neutrality by 2050 through its “Fit for 55” legislative package examined under an accelerated process.

In this context, LCH projects are receiving significant public funding within the EU (e.g. EC, 2022a), its theoretical transverse nature making it an interesting mean to decarbonize certain activities. Such innovations were supposed to be enabled by the EU-ETS that did not produce the dynamic effects expected so far. Further, militarized after the beginning of the Ukraine war, the EU’s massive energy dependency on Russia forced the EC to react. Announced in May 2022, its RePowerEU plan proposes to substantially increase European LCH ambitions, notably by integrating CCfD as a tool “to support hydrogen uptake and electrification in industrial sectors” (EC, 2022b). CCfD aims at creating an additional incentive for operators to invest in low-carbon technologies by reducing the risks associated with the EU-ETS. As this proposal would involve public funding and that this instrument has never been implemented before, it seems relevant to interrogate the potential implications of this choice. Can indeed CCfD be an efficient low-carbon hydrogen innovation support instrument to meet the Paris Agreement commitments? This question entails different conceptions of efficiency: the traditional economic ones (allocative, productive, and distributive) on one part, and the environmental one on the other part.

This work aims to evaluate CCfD functioning and potential effects within the EU-ETS regulatory framework and how their interrelations could affect the former, notably through carbon pricing and the IF institutional setting. For this, microeconomics and the private interest theory of regulation will be used as the main theoretical frameworks. The EC’s goal is technologically targeted, thus development and decarbonization potentials of the LCH technologies need to be evaluated as they will impact CCfD efficiency. Consequently, although building up its analysis on environmental L&E, LCH requires a macroperspective, a succinct techno-economic assessment retaining only LCH’s main technological fundamentals and prospects will then usefully complement the analysis. Ultimately, this work employs an interdisciplinary perspective of the scientific and institutional literature available. It does not account for the entire EU-ETS policy but solely for its features relevant to this analysis. Besides, given the uncertainty surrounding innovation processes and the diversity of methodologies used, costs cannot be directly compared, and the figures used in this work should be interpreted in OoM terms. Furthermore, as the EC has not yet communicated how CCfD would be implemented (to come during Q4 2022), this work is limited to hypotheticals as to its operationality. In this sense, this work aims at analyzing critically the LCH technology and the CCfD regulatory choice for its development, notably examining its consistency with the EC climate ambitions and commitments.

This work is divided into five different sections. Section 1 will introduce the theoretical framework. Section 2 will present a techno-economic assessment of how LHC could lead to GHGE reduction and the related limitations. Section 3 will examine the EU-ETS and how it is relevant for the CCfD implementation. Section 4 will present the CCfD mechanism in detail, offer an analysis of its potential operations within the EU-ETS, and how this could affect LCH developments and EU climate policy. Section 5 will discuss the results before concluding.

**Section 1 Theoretical framework**

 This work is based on microeconomics grounds and public law institutional analysis, which will be presented successively.

**1.1. The microeconomics grounds of ETS**

In microeconomics, equilibrium refers to the archetypal balance between buyers' benefits and producers' costs, allowing price formation in a competitive market. Externalities correspond to collateral costs or benefits produced by one party’s activity to an unrelated third party about the consumption or production of a good or service. They imply that real costs or benefits are not fully reflected in the market price. This distortion leads to market failure as not all the relevant information is transmitted within the market price. Thus, provoking a situation that is not Pareto optimal, consumers are all made worse off because uncompensated by the market for the damage they suffer. To internalize environmental externalities, i.e., to correct the market failure, authorities often resort to public regulations (Faure & Partain, 2019**)**.

 From this perspective, several legal options are possible. Pigou (1920) described economic instruments aiming at orienting behavior positively or negatively, such as pricing the externality, taxing entities responsible for it, or subsiding substitute technologies. So-called market instruments allow this internalization “by returning an appropriate fee or cost to the potential polluter” (Faure & Partain, 2019, p.31). Besides, Coase (1960) offered an analysis of externalities in terms of property rights. Their definition and assignment to the party producing the pollution and the one impacted by it would allow them to bargain and reach a mutually beneficial agreement, provided that transaction costs would be low or inexistent. Building upon both ideas, Crocker (1968) and Dales (1968) proposed a new policy instrument: the emission trading system.

GHGE are a negative externality of current economic activities based on fossil fuels. This harms consumers and hampers future economic growth perspectives. ETS aims at valuing and internalizing emission costs through the “polluter pays principle”. Microeconomics explains that a specific GHGE reduction will be cost-effective solely if the marginal costs of control are equalized for all emitters, these costs corresponding to MAC. By implementing legislative restrictions on GHGE and issuing limited emissions tradable rights, policymakers set up the “rights to pollute market”, supply and demand theoretically defining allowances’ price and reducing information costs.

Babiker et al. (2004) showed that, assuming no distortions, this solution is cost-effective (Figure 1). If policymakers set the optimal total emission reduction at Q\*, the GHGE reduction target is allocated equally between Firm 1 (MAC1) and Firm 2 (MAC2), both lowering GHGE so that Q1 = Q2. The outcome is not efficient as the MAC for Firm 1 is higher than for Firm 2. Assume now that an ETS is implemented: each firm diminishes its GHGE until their respective MAC equals the allowance market price P\* following their respective cost function. At this point, Firm 1 buys and Firm 2 sells emission rights. Ultimately, GHGE are cut by the same amount compared with emission constraints set by policymakers. However, both firms are better off because net income gains are created (triangles A and B), a situation representing an efficient outcome.

If ETS has often been described as the most cost-effective GHGE internalizing solution, “there was and is by no means unanimity about the merits of emissions trading amongst the academic community” (Convery, 2009, p.398). Indeed, some scholars showed that in some circumstances a Pigouvian tax on emissions could provide stronger incentives than other economic instruments for abatement technology adoption (Requate & Unold, 2003). Further, Kaplow and Shavell (2002) settled for *ex-ante* regulation over market-based instruments considering potential long-term damages linked to climate change risks. All in all, numerous factors must be integrated, Fischer and Newell (2008) noting that “an optimal portfolio of policies can achieve emissions reductions at a significantly lower cost than any single policy” (p.144).

**1.2. Economic theories of regulation and the private interest theory**

In this work, regulation would refer to the “employment of legal instruments for the implementation of social-economic policy objectives” (den Hertog, 2010, p.3) to which administrative costs are associated such as agency staff and processes, enforcement, etc. In the field of public law, public interest theory assumes that public regulation, the legislator, and the regulation agency always aim at increasing efficiency and social welfare. Refuting this idea, the private interest theory defends the idea that particular interests orient the preference for regulation or will drive it over time. Notably, associated with the redistribution of wealth, two theories build on this idea: the public choice theory and the regulatory capture theory.

The first one uses microeconomics grounds to explain regulation’s origins. The Virginia School of Public Choice theorized regulation as being inefficient due to rent-seeking extraction possibilities conceptualized as the spending of scarce “resources on political action […] to obtain monopoly rights or other favors granted by governments” (den Hertog, 2010, p.33). Generating a waste of resources to acquire such rights, the monopolist would *ex-post* keep on producing some waste to protect the rights newly obtained against potential competitors, in both ways harming consumers. Developing on the Chicago theories of regulation, it is from this perspective seen as the result of supply and demand on the political market. Regulation is exchanged on this market against political support, which might create a welfare transfer to the interest group. “This rent-seeking behavior will […] be especially successful if […] if the information costs incurred by the public at large to discover the rent-seeking are relatively high.” (Faure & Partain, 2019, p.192)

Secondly, the regulatory capture theory describes a situation in which firms in a regulated sector manage to dictate the regulation agency its purposes (Stigler, 1971), in some circumstances rendering regulation ineffective. This problem arises due to a tradeoff between independence and accountability between politicians and the regulation agency (Maskin and Tirole, 2004). The latter benefits from the resources it has at its disposal to monitor and control the regulated sector or activity, but does not necessarily act benevolently. Two different regulatory captures have been theorized: materialistic (or financial) and non-materialistic (or cultural), the first one referring to monetary advantages affecting the proper regulatory operations, potentially relating to illegal activities, the second concerning the “creeping colonization of ideas” (Engstrom, 2013, p.32). Both capture risks can be mitigated through governance design and a high degree of institutional transparency among other elements. To understand CCfD’s potential for LCH development and GHGE reduction, the next section will assess this technology from a tech-economic perspective.

**Section 2 A source of important GHGE facing technological and economic uncertainties regarding its decarbonization potential**

Hydrogen has a high mass density making it very energetic, but its density is extremely low, which renders it difficult to handle because it is gaseous under normal temperature and pressure conditions. It is naturally found on Earth in proportions that are not yet well defined (Prinzhofer et al., 2018). According to the IEA (2019), hydrogen production has increased more than threefold since 1975 to exceed 70 million tons per year in 2015 and continues to grow. This section will review its current production and consumption modes and those in development to appreciate hydrogen’s climatic impact and LCH’s potential to respond to MS’ commitments under the PA.

**2.1. Current and expected hydrogen production methods**

Firstly, hydrogen is currently transformed via three different methods: TC, pyrolysis, and electrolysis. TC can be broken down into three distinct processes, all of which are based on coal or natural gas associated with high temperatures (between 600 and 1800°C) representing 98% of global dedicated[[1]](#footnote-1) hydrogen production. The first TC method is SMR, during which methane reacts with steam to form a syngas composed mainly of hydrogen. SMR constitutes today 71% of the annual dedicated hydrogen production consuming “about […] 6% of global natural gas use" (IEA, 2019, p.38). The second TC method, partial oxidation, allows hydrogen generation from heavy fuel oil or coal using oxygen. A final TC process is coal gasification, in which the latter is dried and thermally cracked into carbon and hydrogen by an anaerobic reaction. Then, the heated carbon and steam produce a syngas consisting of carbon monoxide and hydrogen. Through the reaction of the gas with water, the carbon monoxide is converted into carbon dioxide and hydrogen. Coal gasification currently accounts for 27% of dedicated annual hydrogen production and "consumes […] 2% of global coal use” (Ibid.). The thermal pyrolysis of methane is the second hydrogen production process. It reduces carbon emissions during the hydrogen transformation process compared to TC. During the thermal treatment of methane in the absence of oxygen, solid carbon and hydrogen gas are produced. Being a highly endothermic[[2]](#footnote-2) process, heat must crack the methane molecules. It is theoretically possible to use a fraction of the hydrogen produced to heat the reactor itself to obtain a carbon-neutral final product. However, its price competitiveness against TC methods is strongly dependent on a higher carbon valuation on the emissions market (Parkinson et al., 2018) and solid carbon by-products must be eliminated representing quantities all the more important as the hydrogen production is high. Electrolysis is the third method currently available for the production of hydrogen. It will be examined in subsection 2.3 together with the technology enabling it: electrolysers. The current global hydrogen production is therefore based mainly on fossil fuels and is responsible for the equivalent of “the CO2 emissions of Indonesia and the United Kingdom combined" (IEA, 2019, p.17) representing about 3% of total global CO2 emissions. It is important to keep in mind that there are many biases and difficulties in the quantitative assessment of all emissions along the value chain, as in the case of methane leaks upstream of the production process often neglected by studies (Noussan et al., 2021). Technological alternatives or complementary solutions are at the R&D stage, e.g., hydrogen filters that prevent other gases from rising during the SMR process (Pflugmann & De Blasio, 2020 p.47) and would have the advantage of using existing infrastructures or the gasification of biomass (IEA, 2018).

**2.2. Current and expected hydrogen usages**

It is also important to look at the uses that are made of hydrogen and those that are anticipated. Hydrogen is employed in four main industrial applications today: "oil refining (33%), ammonia production (27%), methanol production (11%), and steel production by direct reduction of iron ore (3%)” (IEA, 2019, p.89). First, under the pressure of increasing oil demand and stricter air quality regulations, the petroleum sector could see an increase in its demand for hydrogen. Indeed, no substitute is available due to the high temperatures required. Accounting today for about 20% of the world’s CO2 emissions related to refinery operations (Ibid., p.95), hydrogen production, at equal production capacities, could experiment with a shift in CO2 emissions from refineries to hydrogen production facilities. Further, regarding the chemical industry, the IEA states that "hydrogen is part of the molecular structure of almost all industrial chemicals, but only some primary chemicals require large quantities of dedicated hydrogen production for use as feedstocks, notably ammonia and methanol." (Ibid., p.99) Global production of these two chemicals is 65% natural gas-based and 30% coal-based (Ibid., p.100). This production itself generates hydrogen as a co-product of the reactions, which is used in the sector, distributed to others, or released into the atmosphere. The IEA anticipates an increase in demand for these products for their current usages, which would mechanically increase emissions. Finally, the steel sector presents the same hydrogen co-product generation and CO2 releases into the atmosphere. As we see, the current main hydrogen applications also have a high CO2 impact.

Simultaneously, many new applications are being developed and some are already at the commercialization stage. First, some efforts can be seen in the hard-to-abate industries. To reduce CO2 emissions, efforts are being made to use hydrogen as a reducing agent in steel production instead of carbon monoxide derived from fossil fuels (Ibid., p.110). The amount of hydrogen needed for this production could explode, up to 15 times its current level by 2050 according to the IEA (2019). New uses could also emerge in high-temperature industries such as cement. Second, as a secondary energy carrier, hydrogen could be used to generate electricity. The LCH produced thanks to the excess of electrical production generated by intermittent renewable energy sources (such as solar and wind) would reduce the dependence of these technologies on natural cycles (night/day alternation, availability, and speed of the wind, etc.) allowing better management of their electrical supply on the network. The possibility of multiplying local electricity generation units would also benefit from the massification of hydrogen, some solutions being already commercially available. Third, LCH is expected to be used in the mobility sector, both "light" and "heavy". Associated with a fuel cell[[3]](#footnote-3), it can be converted into kinetic energy. In its gaseous form, hydrogen combustion releases only water and no carbon compounds (Van Hoecke et al, 2021). Fourth, LCH is thought to be blended with methane in the domestic gas distribution to lower the related GHGE.

It appears clearly that hydrogen is a highly polluting industrial product, which in turn enables polluting activities. While its potential new production methods and uses could represent substantial GHGE reductions, massive technological and economic challenges still prevent the emergence of a LHC industry.

**2.3. LCH technologies are environmentally and economically inefficient**

Many technologies needed to develop a LCH industry are not yet mature and/or present safety, long-term effectiveness, and environmental concerns. This section will review specifically two of them after analyzing the operational challenges that hydrogen poses. First, LCH poses certain problems that question the capacity to rapidly deploy technically appropriate, safe, and competitive solutions on a large scale. Hydrogen is highly flammable and has a low energy density, which means that its "compression, liquefaction or incorporation [...] into larger molecules" is necessary (IEA, 2019, p.70) to be stored and/or transported. The solutions available today only allow this on a small scale. However, LCH massive production would require operating at a completely different level to guarantee energy supplies. The only large-scale storage solution currently envisaged is geological, in particular in salt caves. Geographically limited, this possibility could also see hydrogen compete with CO2 (see below) for their respective underground storage. Thus, Andersson and Grönkvist (2019, p.11915) conclude that “storage technologies are still being very actively researched, indicating that substantial advances are still to be made” and that “a detailed, accurate economic comparison of all hydrogen options including investment costs is presently not accomplishable." Besides, hydrogen transformation processes allowing easier handling and its transport are extremely energy consuming and still unsafe. Indeed, its liquefaction for instance implies cooling it at -253 °C representing between "about 25% and 35% of the initial quantity of hydrogen" (Ohlig & Decker, 2014). LOHC such as ammonia and methanol can be used but the energy losses induced by the successive conversions imply costs and contradict the goal of carbon efficiency (Anderson & Broderick, 2017). Moreover, as the gases considered are extremely flammable, even toxic (Preuster et al., 2021), many technological and regulatory issues arise to ensure process safety throughout the value chain. Finally, regarding distribution, regional pipelines are the only solution technically available and accessible today at a low cost for large-scale applications. However, being "the smallest molecule [...] [hydrogen] can easily escape through joints and cracks in any piping or storage system" (Van Hoecke et al., 2021, p.834) constituting an additional leakage possibly, thus bringing safety, cost, and environmental concerns.

Secondly, carbon capture presents problems that seem insoluble. CCS corresponds to geological sequestration and CCUS to its coupling with the objective of its (partial) economic valorization. Becoming supercritical[[4]](#footnote-4) beyond a depth of 700m (UNECE, 2021, p.7), four types of geological reservoirs (OECD/IEA, 2016, p.32) would allow retaining the CO2 as it mineralizes over geological periods. The availability of such storage capacities is spatially limited. Their geographical distribution is uneven from one country to another, requiring international coordination for CO2 conditioning, transportation, and sequestration. The implementation of a specific governance system is therefore necessary (trading platforms, specific regulatory frameworks, and procedures). CCS expected GHGE reduction potential is up to 90% in hard-to-abate sectors (IEA, 2019, p.39) even though being itself an energy-intensive process (OECD/IEA, 2016, p.28). Although CCS appears to be technically mastered, certain risks remain. First, they relate to the possibility of leakage due to several factors. Seismicity and accidents remain risks even though they are integrated into the choice and design of storage sites. Most importantly, installations securitization and sequestration duration cause concerns. The airtightness of storage sites is in theory geologically assured as reservoirs were stable for millions of years. To control the eventuality of leakage, CCS requires the implementation of monitoring systems to ensure over the very long term that the reservoir remains sealed. Second, financial risks are also a limitation. CCS represents significant investment costs that will be contemplated only with the right incentives are in place. Water availability near project sites (Noussan et al, 2021) and the energy consumed for the CCS process (The Royal Society, 2018) significantly influence projects’ profitability for instance. The failure to establish carbon pricing mechanisms that orient investments through sufficient signaling also accounts for this inertia. Third, these uncertainties and risks fuel social resistance. Indeed, opposition movements have arisen, and some governments have limited CCS, or even banned it, due to legal, health, and environmental considerations. As a result, within the EU only 35 CCS projects are under development and the first one approved for commercial use, Porthos in the Netherlands, was confirmed in May 2022 (Global CCS Institute, 2021). To sum up, CCS’s contribution today is negligible compared to the 38Gt of CO2 released into the atmosphere in 2019 linked to energy uses (UNEP, 2020). Regarding CCUS, it is interesting to note that CO2 is already employed in the oil industry to optimize the yield of wells, this option being actively promoted by international bodies (UNECE, 2021, p.9). Thus, in addition to offering an option to reduce their carbon footprint, the extension of CCS techniques also represents a possibility of extending their activities with high GHGE impact, which is again inconsistent with the emission reduction objectives. Other possible uses of CO2 are put forward, notably for the concrete manufacturing process.

 Third main technological solution essential for LCH massification, electrolysers are still inefficient and costly. Electrolysis is a process that consists in separating the dihydrogen and oxygen that make up the water molecules by passing a direct electric current into it. The hydrogen production process using this method is in itself low-carbon. Holding electricity consumption constant, the installation of electrolysers, therefore, implies an increase in electricity production to operate them. The source of electricity is a crucial element to consider. If the production of electricity were itself a source of GHGE (45,5% of the total net electricity production in the EU-27 came from fossil fuels in 2018), the generation of LCH would not fulfill the assigned function of decarbonizing activities. Thus, the electricity needed to power the electrolysers must come from low-carbon sources. This need for abundant production of low-carbon electricity raises some questions. Indeed, Deshaies (2020) notes that "the main limit to the substitution of renewable energies for fossil energies is their low power density, which forces us to install production capacities 5 to 10 times greater than those existing in fossil energies”, which forces us “to exploit considerable areas […] which is not possible in densely populated European countries. [...]”[[5]](#footnote-5). In this way, land artificialization in the EU could lead to a positive carbon footprint if previous land occupation allowed a higher carbon sinkage. Also, the improvement of renewable energy systems’ load factor with the development of the technology is compensated by the diminishing returns of the land exploited, the most productive ones having been used first. Consequently, countries that are heavily dependent on fossil fuels for their electric production, such as Germany are currently working to secure international partnerships for massive quantities of renewable electricity or LCH produced by countries with significant solar and wind energy potentials, such as Morocco or Chile. An intrinsic contradiction in this import configuration is the availability of water in the countries previously referred to. Indeed, climate changes accentuate water scarcity in areas used for photovoltaic electricity production because of their sunshine. The lack of water is potentially an obstacle to electrolysers deployment in the long term (Noussan et al., 2021). And as we have seen, LCH transport involves high energy losses. Moreover, prohibitive costs augmented by an extremely limited electrical production capacity hamper electrolysers massification. These costs are high compared to fossil fuels-based solutions due to the price of electricity used as an input. Moreover, the power-to-gas-to-power configuration (allowing LCH production from electrolysis to be after that reinjected into the grid) currently has a low energy yield of around 25% as electrolysers capacity remains limited, around 1 MW (Ibid.). As a result, "switching the current annual EU hydrogen production of 9.75Mt to electrolysis would require 290 TWh of electricity (about 10% of current production)." (Kakoulaki et al., 2021, p.9) Finally, current electrolysers technologies currently rely on rare metals extraction (scandium and iridium in particular), which is a polluting process. Their supply is also small, highly concentrated, limited to a few countries, and untransparent, therefore representing a risk (DERA, 2021). Considering these elements, the possibility of electrolysis allowing for a large LHC production is extremely limited, not even to mention rapidly to meet commitments made under the PA.

Hydrogen is therefore a product responsible for significant GHGE. The technologies on which LCH projections are based are still in the R&D stage. If LCH has the potential to lower GHGE of hard-to-abate industries and to be used as an energy storage solutions for the electrical surplus produced by renewable electricity technologies that cannot be used immediately on the grid, its energy efficiency is problematic. Indeed, energy losses implied for its transport, storage, or use imply significant costs. Beyond the economic calculations, such wastes involve increased GHGE compared to alternative technologies. Further, hydrogen allows the extension of activities based on fossil fuels, allowing for their extension. These features as well as the energy infrastructure investment timeframe seem incompatible with the urgency of climatic action to meet PA’s objectives and the immediate GHGE reduction they imply. Considering these elements, we can now assess the EU-ETS mechanism and its effects so far to support technological change.

**Section 3 EU-ETS: a regulation under the influence that began to operate properly recently**

Implemented by Directive 2003/87/EC (EPC, 2003), the EU-ETS set a cap on GHGE by issuing EUA permitting the emission of one ton of CO2 covering only a few sectors. The total amount of EUA was planned to be gradually reduced. Emitters must either reduce their emissions or buy allowances from other firms. Emission reduction can take the form of investment in low-carbon solutions, efficiency improvements, or production decreases. The EU-ETS began to operate in 2005 and was organized in years-long phases to induce predictability. It is currently the “largest carbon market in the world and first transboundary cap-and-trade system” (Borghesi & Montini, 2016, p.3) covering over 14000 “installations” (including within European Economic Area flights) representing about 36% of the EU’s emissions (EEA, 2022). As Faure and Partain (2019) state, market-based instruments can be affected by “design issues that can reduce their effectiveness“ (p.201) and are “susceptible to lobbying that also affects instrument choice and design.” (Ibid.) This section will explore successively how both issues altered the EU-ETS and how this is relevant to its environmental efficiency through EUA price formation, the latter being a central element of CCfD.

**3.1. EU-ETS design deficiencies**

 This subsection will describe the scope definition and governance flaws that have affected the proper functioning of the EU-ETS.

**3.1.1. An initial scope definition under the influence**

For different reasons, some industries were excluded from the regulation’s scope or were granted free allowances resulting from conflicting and intertwined determinations at several levels. First, *de minimis* rules exist, small emitters arguably do not have the same capacity as important ones to deal with the transaction costs the EU-ETS implies. This exclusion has been made optional for installations emitting less than 2 500 tons in revision Directive (EU) 2018/410 (EPC, 2018). Second, some decisions can be explained using jointly public choice and regulatory capture theories, Mildenberger calling this convergence the “double representation of carbon polluters.” Following a demand for environmental regulation coming from multiple parties, EU politicians decided on a market-based instrument requiring extensive regulatory design as a “prototype” (Ellerman, 2009). The need to protect firms, gain their support and avoid production relocations created a bias that was used to grant extensive exemption rights to EU-ETS rules. Indeed, EU producers face higher costs than third countries competitors due to their ETS obligations, these competitors would have had the possibility to free-ride on the EU’s voluntary climate policy, creating a risk of carbon leakages. Politicians became the voice of their respective country’s carbon/energy-intensive industrial interests, differences between MS’ “climate policymaking trajectories [reflecting] institutional differences in carbon polluter influence on policy design.” (Mildenberger, 2020, p.41) Germany is illustrative of this dynamic, having secured in 2008 free allowances for the steel, cement, chemicals, and coke industries (Skjærseth & Wettestad, 2009) which “created the contradictory situation of Germany being both leader in the clean energy domain despite supporting forcefully the coal industry” (Mildenberger, 2020, p.208). These industrial groups’ influence implied important consequences for the EU-ETS. Considered an inherent contradiction of emissions trading, grandfathering is justified to prevent relocations but parallelly erodes the credibility of the EU’s climate policy by indirectly subsidizing polluters for polluting (Nash, 2000). Consequently, competition distortions within and across sectors in the EU as well as between MS to defend their national industrial interests were created or exacerbated by this initial regulatory design (Quirion, 2021). In particular, larger emitters, such as energy generation sectors, benefited from massive windfall profits (Cludius, 2018) and have created a lobby to preserve their rent (Fuchs & Feldhoff, 2016). These regulatory choices underestimated the dynamic effects, thus undermining the EU-ETS’ efficiency.

**3.1.2. Governance flaws in the first EU-ETS phases**

Important governance problems were identified for the EU-ETS’ initial phases. First, as generic rules were applied differently by MS, it resulted in over-allocation of allowances. This was due to differentiated national energy policies (Sijm, 2005), variations on new installations and closures transfers policies, application of different benchmarks, and MS acting distinctly regarding how to account for firms’ previous climate actions and related free allowances. This situation generated a “lack of adequate stringency” (Borghesi & Montini, 2016, p.3), reinforcing competition distortions created by grandfathering. Second, transparency and monitoring problems led to frauds such as allowances disappearance from national registries or VAT fraud (Frunza et al., 2011) that weakened the EU-ETS’ overall efficiency. To resolve these issues, a centralized Union Registry for allowances was established by the EU Regulation 389/2013 (EC, 2013). Further, the allocation decision was assigned by Directive 2009/29/EC (EPC, 2009) to the EC, which is setting the cap since phase 3 (2013-2020).

**3.2. EUA price formation, evolutions, and predictability**

Characterized by its volatility and low price since its inception, the mechanism can still have the possibility to incentive behaviors by its very existence, but it is not an optimal result (Faure & Partain, 2019). EUA price which increased strongly over the past year is influenced by drivers that are both endogenous and exogenous to the system.

**3.2.1. Endogenous factors**

On one hand, several endogenous reasons have been identified that contribute to explaining these phenomena. First, the imbalance between demand and supply has influenced negatively price formation, with institutional design deficiencies and the governance issues and scope definition seen previously contributing to this. It has also been shown that “*ex-ante* expectations tend to overestimate the constraint” accounting further for excessive allowances emissions (De Perthuis & Trotignon, 2014). Moreover, the large import of offsets at the end of phase 2 pushed the price down (Borghesi & Montini, 2016). Second, the regulatory uncertainty related to long-term EU climate policies, particularly emission targets, also affected the price formation by reducing the demand (Egenhofer et al, 2012). Third, the overlap of the EU-ETS with other policies such as renewable support schemes rendered the incentive framework ambiguous (Koch et al., 2014). To address the surplus of allowances issued, the back-loading initiative was introduced by the EC (2011; 2014) consisting of deferring the scheduled auctioning of allowances to reestablish a supply and demand balance during phase 3, expressing the need for a more permanent solution. Further control was materialized in 2019 with the implementation of the MSR (EPC, 2015), which also assumes the role of improving “the system's resilience to major shocks by adjusting the supply of allowances to be auctioned” (EC, n.d.). Reforms were welcomed as providing more visibility and flexibility to the scheme, the EUA price evolution has however been erratic since then, the MSR establishment decision only having a marginal effect on the price.

In the context of the Covid recovery, the EC (2019b) has strengthened its climate ambitions after having announced the Green New Deal in December 2019. Including them in its “Fit for 55” (EC, 2021a) legislative proposal package announced in July 2021, it aimed at a new EU-ETS reform. This contains different aspects: an increase of the linear reduction factor, adjustments of both the MSR’s intake rules, the Cancellation Mechanism’s threshold, the phasing out of grandfathering between 2026 and 2035, and the creation of an ETS2 covering road transportation and buildings to be implemented on the same timeline. It aims at increasing predictability, reducing volatility, and would strongly reinforce the overall stringency of the market. This announcement caused the EUA price to suddenly increase in proportions never seen before. Wildgrube (2022) identifies this parameter to explain more than 95% of the price evolution for 2021, even though these new rules have not even voted on yet. Therefore, regulation drives the market supply and the regulatory framework’s modifications are anticipated by the agents with larger price effects than the market transactional activity. The regulator is by design a market maker through its structural supply signaling power, contradicting the very idea of the ETS model as a market disconnected from its fundamentals: regulation. Public authorities initiate the EU-ETS through enforcement and guidance and interventions should not exceed the optimal level (Sorrell & Skea, 1999). However, there is a trade-off between predictability and reactivity: the first is designed within the regulation and aims at substituting the economic dynamic of the market coordination, and the second is the underlying price formation’s determinants, especially exogenous ones. Despite the affirmation of the EC, the MSR’s objective to “improves the system's resilience to major shocks” and its operations based solely on pre-defined rules leaving “no discretion to the Commission or Member States” (EC, n.d.) seem strangely misplaced in the case of a shock as it could indeed require specific interventions. Further, the EC can always modify these rules and/or the scope/extent of their application through legislation. Rules cannot resolve the intrinsic risk regulation bears. On top of these endogenous dynamics, the EU-ETS is influenced by fluctuations and trends coming from the macrolevel.

**3.2.2. Exogenous factors**

On the other hand, some exogenous factors have been mentioned as influencing the EUA price evolution. First, the effect of the 2008-09 economic and financial crisis and the recession if provoked has been well established to explain its fall (Koch et al. 2014). This situation could reiterate with the appearance of a new recession. Second, Fields and Lindequist (2022) have highlighted regulatory risk spillovers as the EUA price seems also affected by US climate policy announcements. Third, a sound price trend correlation with fossil fuels energy markets has been demonstrated, Lovcha et al. (2022) evaluating an on average 65% positive linkage between the energy markets and EUA price fluctuation between 2008 and 2018. They also suggested that the main drivers of uncertainty evolved from economic activity and gas hub prices to oil and coal over the period, concluding that the EU-ETS has started to operate properly, the ways and extents to which the information is transmitted from energy markets to the EU-ETS not being established. Moreover, Dai et al. (2021) find an interplay between carbon and energy markets during higher-moment orders, which enhances a bullish market.

If this linkage is intuitive, as the EU-ETS is supposed to deter fossil fuel usage through the signal of EUA price, thus evolving parallelly to create an incentive, it could also imply a retroaction, namely that shocks experimented by these underlying markets would be repercussed into the EU-ETS. This interplay and how it operates is probably not unilateral and, as mentioned, not entirely understood for now. However, given the structural and potential reciprocal influence between energy markets and the global economy and their strategic nature, geopolitical events affecting energy markets would have the possibility to impact the EU-ETS. The Ukraine war and the following EU’s determination to substitute its fossil fuel imports from Russia, notably through its RePowerEU plan (EC, 2022b), impacted energy markets as well as suddenly incorporated geopolitical and geostrategic considerations into the EU climate policy. Questioning the discourse on the doux commerce theory, both events were a source of volatility for the EUA price as the first quarter of this year suggests. Further, volatility could be a prospective characteristic of fossil fuels energy markets due to new geopolitical shocks for instance representing an enhanced risk for the EU-ETS.

**3.3. Dynamic and environmental efficiency results**

Aiming at supporting technological change to improve environmental efficiency, the EU-ETS has not so far demonstrated great performance. This section will review each category successively.

**3.3.1. Induced innovation and competitive process**

Innovation is an explicit objective of the EU-ETS to support technological substitution, specifically “eco-innovation” of product, process, and organizational as defined by Kemp (2010). Induced innovation is a concept hypothesized by John Hicks, who explained that a “change in the relative prices of the factors of production is itself a spur to invention” (1932, p.124). In this respect, the EUA price signal is critical. But the innovation is also supported financially. Article 10a(8) of Directive 2003/87/EC (EPC, 2003) established the 300NER program, which aimed at developing demonstration of environmentally safe CCS and innovative renewable energy technologies on a commercial scale. Marcantonini et al. (2017) explain that the IF (EC, 2019c; EC, 2021b) was designed to replace it and reinforce incentives for innovation and investment. In particular, it broadened its resources and the eligible beneficiaries. Among others, the maximum funding rate was raised to 60%, more financial instruments were made available, achievement of milestones now determines fund disbursement, and projects are evaluated not on their sole efficiency but also according to cross-sectorial cooperation.

EU-ETS innovation effects are complicated to assess as they are interwoven with many other dynamics, the challenge being that we can only assume what the emission levels would have been without its implementation, Calel (2018) states that there is a lack of understanding regarding how policy induces innovation and Popp (2019) shows that policy incentives can even affect agents outside the territory an environmental policy applies in. Nonetheless, the analysis showed that its efficiency could be improved as innovations induced by the EU-ETS were deemed as positive but weak. Teixidó et al. (2019) highlighted relatively stronger effects on low-carbon innovation developments than their adoption for the first two EU-ETS phases, Borghesi and Montini (2016) adding that they can be measured both at the EU and individual MS levels. Marcantonini et al. (2017) showed that related patenting and R&D expenditures increased but that projects implicated were typically small-scaled with short amortization times. Explanatory elements included first price volatility, which would have deterred investment in low-carbon technologies, the market signal not being stable enough (Gronwald & Ketterer, 2015). Similarly, a too low price rendered financing costs too high for low-carbon technologies. Further, MS’s unilateral national policies to support a wide range of eco-innovations could have created allocative alterations between them as the EU-ETS caps emissions, a phenomenon referred to as the “waterbed effect” (e.g. Eichner and Pethig, 2019). Besides, if the EU-ETS appears to act as a signal for technological change integrated by the agents, it does not seem to trigger it. Martin et al. (2016) show that if innovation development is stimulated, its adoption is not.

**3.3.2. Environmental Efficiency**

Nevertheless, environmental impact is even more controversial. Indeed, it is difficult to differentiate the EU-ETS driving effect from other simultaneous phenomena or to distinguish between the respective impacts of different factors. The reduction of GHGE in covered sectors is announced to have declined by 35% between 2005 and 2019 (EC, n.d./b) and is partly confirmed by some studies (e.g., Martin et al., 2016; Bayer & Aklin, 2020). An optimal resource allocation would have ensured a larger GHGE reduction. If this could appear as quantitative success, several shifts in its basis of calculation, as well as their mutual influence, tend to temperate these results. Indeed, the main emissions abatement part between 2005 and 2012 is attributable to the impact of the economic crisis and EU-ETS contribution seems much lower than expected (Bel & Joseph, 2015). In any case, the enlargement of the EU and the economic recession were crucial drivers for EU emissions abatement (Borghesi & Montini, 2016). Furthermore, the effect on GHGE has been moderate when compared to the targets set by the Paris Agreement (Green, 2021). In this respect, the EEA estimates that “current ETS projections do not show the reductions in emissions needed to bring the ETS into line with the new 2030 target and to set EU emissions on a path to achieve climate neutrality in 2050.” (p.5) Moreover, rebound and shift effects other than geographical ones (carbon leakages) could be observed in the future, the energy supply consequences of the Ukraine war in the EU being an example.

Qualified as an “administrative nightmare” by Baldwin (2008), the EU-ETS proved him to be right. As stated by Sato et al. (2022), the EU-ETS regulatory design is a “complex tug-of-war between environmental ambition, principles of aggregate economic efficiency, and the politics of distribution” (p.3). Even though the EC defends the point that EUA price should not “become primarily a product of administrative and political decisions (or expectations about them), [but] rather than a result of the interplay of market supply and demand” (EC, 2012, p.10), the regulator owns an unchallengeable market power. EU-ETS tends to stabilize its operationality through better mechanisms allowing for its “free price under constraints” formation to being more predictable to ease agents’ anticipations. Reduced volatility would allow the system to ensure financial foreseeability for LCH and other eco-innovative projects financing and, together with a higher price, their viability. If the war in Ukraine accelerated the EC’s proposal of CCfD for LCH, it did not change the legal or institutional fundamentals of the EU-ETS. Section 4 will now examine this contractual mechanism.**Section 4 CCfD to boost LCH in Europe, an efficient instrument?**

****Hydrogen represents the major sector being supported by the IF and is present in other of its projects. Its first large-scale call (LSC) to projects attributed an average of 157 million euros per project, the related agreements having been signed in Q1 2022. The second one will involve a 1.5 billion euros investment and grants awarded should be communicated in Q4 2022. As seen, the EUA price remains too low to allow a viable business case for large investments in LCH technologies. Because of this and to substitute EU’s reliance on Russia’s energy imports, the EC announced a doubling of both its 2020 LCH production target for 2030 and IF’s capitals for its third LSC starting in Q1 2023 as well as the implementation of CCfD (EC, 2022b). First proposed by Helm and Hepburn (2005), CCfD is presented as an additional incentive tool for the IF to support innovative projects by removing remaining technological and financial risks. If it is a theoretical attractive instrument, the practicality and implications of its implementation could prove to be more complicated.

**4.1. An attractive instrument to reinforce projects’ financial viability**

CCfD are contractual arrangements through which public authorities agree with an agent on an *ex-ante* fixed EUA price, called strike price, over a given period. The agent can sell the EUA. At the end of the period, if the price market is lower than the strike price, he receives the difference from the government protecting him this way of low-carbon price risks. Conversely, he must pay the difference to the public authority if the market price is higher. CCfD help to provide more stable and viable financial business cases by lowering operators’ risks related to EUA price volatility.

The literature identifies several positive effects CCfD could have. It offers potential for recuperation of costs for governments as the carbon price rises. Besides, Chiappinelli and Neuhoff (2020) have underlined that establishing a contractual relationship offers the agent further security in terms of public commitment to not expropriate the rent of innovation *ex-post* by lowering the EUA price. This possibility anticipated by the operators would hamper their investments in low-carbon solutions. This way, CCfD offers clear signaling regarding government policy intentions. Also, it allows compensation for operators for the regulatory risk linked to long-term climate policies, which translates into uncertainties in carbon price futures. Further, Newell and Fischer (2008) have shown that EUA prices might not provide the proper incentives when knowledge spillovers characterize the innovation process. CCfD in this perspective is seen as a mean to support projects facing innovation market failure over conventional technologies, feature reinforcing the signaling for innovation. Moreover, Neuhoff et al. (2019) showed how CCfD allow for a higher debt ratio, reducing both the EUA price required to make the investment competitive and the public co-funding. The volume and technology risks are also mitigated when combining CCfD with up-front innovation funding (Richstein 2017). Therefore, CCfD appears as having the capacity to foster LCH innovation should EUA price would not reach a sufficient signal level.

 As a support mechanism, CCfD need to be compliant with EU competition law and WTO rules. Sartor and Bataille (2019) argue that at the EU level it would not be considered a state aid as aiming at innovation of general interests but would require coordination with national support policies. Further, they underline that even if politically sensitive as touching national strategic areas, it would also allow further integration of the single market. It could be used to complement both national and EU innovation funding as well as the CBAM by investing its potential revenues in developing countries. This in turn would “foster energy security, partnership development […] more aligned with WTO rules” (CFMP, 2020).

**4.2. An unbalanced risk allocation**

CCfD proceed to a risk allocation which is completely transferred to the public authority and acts at different levels. The first aspect is CCfD duration. Key of the risk coverage, it also is a risk in itself as part of the insurance mechanism. Together with direct technological support and the possible risk of failure of the same (CFMP, 2020), it appears to be the best-balanced element in the risk allocation between the parties, but duration still requires careful consideration, large-scale projects supported by the IF being covered for 10 years. Neuhoff et al. (2019) suggest a duration of up to 20 years, which seems excessive given EUA price evolutions as well as the foreseeability of events for such time horizon. Second, parameters influencing the EUA price and their trend need to be assessed. The regulatory framework in which CCfD would be implemented, i.e. EU-ETS, is by design intended to strengthen its cap over time additionally to currently experimenting with a clear tightening, questioning the allegedly risk-sharing nature of CCfD. As they would be based on EUA price, the definition of the strike price would probably impact it by retroaction. Indeed, whether negotiated or determined through auctions, the information would be interpreted as anticipations of the same due to the medium or long-term basis of the contractual framework. Rendered public, it would undoubtfully influence the EU-ETS market, particularly as most projects and agents covered by CCfD would be large players. This would participate in blurring even more causal linkages and drivers of EUA price.

If the regulatory risk is oriented in one direction as we have seen, this could evolve in the future particularly as exogenous risks remain and could impact the payment determination of CCfD. From this perspective, a recession is in the long run a certainty and could impact negatively the carbon market as the 2009 crisis did. In the case of a global recession, a downward trend would be feedbacked in energy markets. This situation would expose governments to conjectural higher costs and higher compensations for operators at a moment that could prove to be budgetary delicate. Nevertheless, the contrary is not excludable, i.e. the increase of EUA price during a recession. This situation would provoke payment to the government from the operators which represents the concretization of the public authority protection but exposes operators in hardship times unless producing energy themselves. This dynamic could potentially jeopardize projects reaching the opposite effect than the intended one. Besides, energy markets are notoriously uncertain and particularly volatile for a few years, which would affect EUA price.

Furthermore, both endogenous and exogenous risks could potentially be confronted with defenses strongly founded as their argumentation would be supported by the objectives the IF would have aimed at. On one hand, the regulator being both party to the CCfD and judge as overseeing the design of EU-ETS’ rules, operators could back out of CCfD under unconscionability due to the disproportionate power the regulator would have *ex-post*. On the other hand, in the case of exogenous factors affecting the EUA price, public authorities could evoke impracticability contracts due to unforeseeable circumstances. This could for instance apply to geopolitical events altering positively energy markets or to the deep detrimental effects of an economic recession. Both situations would have the potential to jeopardize the viability of projects covered by CCfD, the contractual mechanism however offers operators the possibility to rely on public authorities to recoup part of their investment. These defenses could incentive risk-tolerant financial investment behavior from both sides.

**4.3. Institutional risks related to the technology**

First, defining LCH and related technologies is problematic. As it requires electricity for its production, the EC declared that an additionality principle should guide LCH production, i.e., electricity used for this purpose would have to be sourced from new dedicated low-carbon installations to avoid further use of fossil fuels. If rather logical with the aim of maintaining the overall EU productive output and its climate ambitions, this principle however represents a tradeoff with both the geostrategic and climatic urgencies at hand claimed as being priorities. What is more, limits are unclear regarding what corresponds to LCH. Should the primary energy source be used as a reference or a certain level of GHGE and, if so, over which section of the productive process? A consultation was held until June 17th, 2022 over these topics and the EC is to release its final legislative proposal by Q4 2022. However, the draft presented in May 2022 with the RePowerEU plan showed a strong issue. Indeed, it would apply only from 2027 allowing a grandfathering of actual capacities, and this without limiting the possibility of contracting them for future supply. This potential flaw would allow for exactly what it tries to avoid: an increase in fossil fuel use and therefore GHGE linked to hydrogen generation. Interestingly, this was part of the hydrogen industry’s demands to the EC back in December 2021 (Hydrogen Europe, 2021).

Second, the information asymmetry is particularly complicated in the case of CCfD for hydrogen. As seen, LCH offers transversal applications, complexifying all the more innovative projects. Indeed, the synergies and complementariness of these solutions, themselves based on state-of-the-art technologies, imply very technical and specialized knowledge. Consequently, the knowledge required to properly assess them is cross-sectorial and more than proportionally augmented compared to the number of actors/industries involved. This reduces all the more the pool of experts capable of conducting such an evaluation in turn diminishing the IF’s ability to recruit competent professionals. Thus, the probabilities of conflict of interest and regulatory capture are multiplied. Even though mitigation strategies are in place, such as recruitment selection, mutualization of information at the EU level (e.g. Joint Research Center and industry benchmarks), or through project evaluation, the inherent tradeoff between knowledge and impartiality remains. This scarcity is even explicitly anticipated by the EC as experts are immediately excluded when considered in direct conflict of interest unless “participation is justified by the requirement to appoint the best available experts and by the limited size of the pool of qualified experts” (EC, 2022d, p.3). To sum up, there exists an expertise deficiency that dramatically increases the possibility of conflict of interest and the risk of capture.

Third, the EC communicated that CCfD would be focusing on specific fields, namely LCH and electrification, which can weaken the IF authority. This emphasis contradicts the technological neutrality principle, which the EC in its impact assessment for CCfD implementation within the EU-ETS reform, maintained as fundamental (EC, 2021c, p.65). Competitive processes should describe the result to be achieved without specifying the technology to be employed. This principle is a cornerstone in institutional innovation support operations to ensure the selection of cost-efficient solutions. Even though no official regulation is available yet, some documentation from the IF tends to show that this will be put in motion as it “will become more focused […] [on] innovative electrification and hydrogen applications in industry.” (EC, 2022e, p.7) The competitive process should be organized both throughout sectors and “the circular economy (e.g., having primary steel decarbonization options compete with secondary steel), taking therefore into account the resource intensity criterion” (CFMP, 2020, p.6). Again, if a tradeoff exists in public innovation support between selection and efficiency, CCfD as presented is an instrument aiming at supporting different technologies at different stages along the learning curve would contradict the technological neutrality principle. Indeed, type I and type II errors would undoubtedly happen: orienting the market toward particular solutions through public support policies to the detriment of potentially more efficient ones.

**4.4. Anticompetitive effects**

 Each of the three phenomena described above bears competition distortion effects, offering possibilities for the operators to exert market power in the competitive process. This would allow the awarded parties to extract rents from it. Further, these distortions potentiate one another and reinforce others. First, CCfD could have anticompetitive effects by themselves. As a subsidy, it could create a barrier to entry for newcomers, CCfD representing an additional administrative requirement that would favor incumbents and big players on top of being a financial support. If competitive processes try easing this effect, there is an inevitable risk of administratively selecting operators through tenders. Given that the EUA price has a more significant impact on large projects’ investment decisions, as the ones that would be required to scale-up LCH, the biggest operators would be favored by CCfD implementation compared to newcomers and smaller ones (Sartor & Bataille, 2019). As the structure of energy markets is oligopolistic and composed of operators of significant size due to the required large and long-term investments, CCfD would reward their ability to assume these risks, thus increasing the potential for both regulatory capture and market distortion. This could lead to locking in incumbents in contradiction with EU competition rules, further enhancing well-identified effects of environmental public regulations (Faure & Partain, 2019, p.209). Besides, this could incentivize collusive behaviors through *ex-ante* anticompetitive agreement over the strike price for instance. Second, payments made under CCfD, which operates as an indirect financial subsidy after the contractually determined period expires, would also have a distortion effect regarding competitors. Third, CCfD would imply reinforced distributional effects within the EU. As covering for an increasing cost respective to the project’s size, it can enhance the EU-ETS’ disproportionate effects between and within countries, particularly towards low-income countries under current phase 4 rules (Landis et al., 2021). Fourth, cross-market anti-competitive effects would be possible due to the industrial transversality of LCH. Fifth, public authorities’ choice of the adequate level of implementation is always important in environmental policies, particularly as a lack of coordination between MS could generate distortions and costs similar to the ones seen during EU-ETS phases 1 and 2.

**4.5. Correctly Pricing the Carbon to Evaluate CCfD Opportunity**

International bodies like the WB (2017) or the EBRD (2020) through quantitative projections proposed a carbon price of “at least US$40–80/tCO2 by 2020 and US$50–100/tCO2 by 2030” (p.3) to impulse technological change. Similar cost estimates have been produced by scholars like Sartor and Bataille (2019) who ensured that CCfD would allow for the “CO2 price faced by investors […] [to] better reflects the true social cost of carbon in the economy [and] would complement the EU ETS by providing a sufficiently high and predictable carbon price” (p.9). They estimated breakeven CAPEX and OPEX costs for some low-carbon technologies, including some LCH developments as well as the potential cost for some energy-intensive industries in France. The carbon prices considered as providing enough price signal for each technology have also been largely overpassed since November 2021 without showing a strong reactivity from the industrial sector so far. If previous volatility and inertia due to energy installations life and investment timeframe can explain this, Germain and Lellouch (2020) calculations establishing the social cost of carbon much higher than previously evaluated contribute to this phenomenon. Indeed, as a conservative estimation, they calculated it to be around 250€/tCO2eq for France in 2020, which is about threefold the current EUA price. The methodology they applied included elements left aside but mentioned as important by the group led by Stiglitz for the WB. This figure, if applied to the EU-ETS policy to indeed internalize the carbon externality as efficiently as a carbon tax (Green, 2021), could create the powerful incentive the EU-ETS has been initially officially designed for.

 CCfD plurality of nature within the EU-ETS, both the carbon price hedging tool and innovation subsidy, makes it difficult to apprehend. Based on the EUA price, it however operates outside its field to increase the financial viability for operators at the detriment of the public interest and without counterparts or guaranties of any sort. Even though its potential benefits are clear, its pitfalls could prove to be disastrous, as the following section will suggest.

**Section 5 Discussion**

EC’s choice to fully support LCH seems in contradiction with environmental efficiency, as we have seen. The inclusion of CCfD in climate policy appears as an pressured response to the geopolitical and energy emergency, not a climatic one. If additional incentives must support eco-innovations, CCfD does not seem to be the most adequate one. Other policy choices are available, particularly some allowing a greater GHGE reduction impact and ultimately economic efficiency.

**5.1. LCH: a choice based on economic strategic behavior rather than environmental efficiency?**

First, considering the mentioned technological limitations and energy inefficiencies of LCH, this technological choice does not seem to fit the IPCC double “immediate and deep” decarbonization criterion. The impact of hydrogen as a GHG is unclear as it has not been identified as an important climate forcer until now but is far from “greenhouse consequences and would not be free from climate perturbations” (Derwent et al., 2006, p.1). This could change with its massification and recent studies tend to show that its impact on the climate has been previously minimized (e.g., Ocko & Hamburg, 2022). Besides, Jorgo Chatzimarkakis, director of Hydrogen Europe who represents the European hydrogen industry, stated that the RepowerEU objectives “would require an electrolyser capacity of 320.000 MW - compared to the EU Commission's H2 strategy of 40,000 MW from summer 2020. The capacity worldwide would be just 3,000 MW” (Lütkehus, 2022). The need of sufficient low-carbon electricity supply that would need to be produced parallelly in compliance with the additionality principle would be another huge challenge. Further, CCS does not correspond to a carbon-neutral activity and entails several very significant risks. Financial commitments to be bearable must be foreseeable by the private actors, which imply a limited duration of their burden. Nonetheless, the time scales on which CCS operates intrinsically contradict their need for visibility (on this and below CCS legal considerations, see Akerboom et al., 2021). Further, the Directive 2009/31/EC stipulates that when wells are sealed, operators remain legally responsible for their monitoring for 20 years. If an operator is unable to take the necessary corrective measures in the event of a leak, the responsibility passes to the "competent authority". Public authorities would thus find themselves assuming the obligation to manage possible failures without having access to the relevant information or possessing the appropriate technical expertise. Moreover, if the leak would turn out to be massive, CCS could represent a danger to populations and even lose all environmental interest. Therefore, the definition of a regulatory framework providing the right incentives seems difficult to establish, particularly as the detrimental effects of a massive leak would be global by nature with potentially unlimited litigants. Enforcement through corrective measures and penalties in such a case are also difficult to conceptualize. This possibility would render its environmental impact enormous and its efficiency negative. Also, despite being presented as an essential tool for decarbonization, the “current pace of CCS deployment is out of step with Paris ambitions […] and is inconsistent with a 2°C pathway, let alone one well below 2°C” (OECD/IEA, 2016, p.11). Moreover, electrolysers technology bears the potential for a new dependency through metal supply, which is exactly the kind of dynamic the RepowerEU plan is trying to eliminate.

 Therefore, secondly, impelled by the Ukraine war, EC’s full support to LCH questions the motives behind this decision. The EU is the more advanced bloc on the related technologies and has shown its clear interest in developing a new industrial sector that would give it energetic independence and security. The experience of PV production delocalized almost entirely to China has left its mark. Therefore, the acquisition of a first mover advantage within what is already called a global LCH race (Van de Graaf, 2021; IRENA, 2022b) seems at least as much important in the RepowerEU announcement as innovation and energy supply securitization. It seems clear that the objectives envisioned by the EC are not focusing on environmental efficiency. Incorporating geopolitical considerations for both energy supply security and sovereignty appears to contradict its sustainability goal, i.e. PA climate commitments, in an “impossible energy trinity” (Thaler & Hofmann, 2022). Moreover, a Harvard study (Nuñez-Jimenez & De Blasio, 2022) has shown that importing LCH would be cheaper for the EU than producing it eventually.

**5.2. CCfD: a misled and counter-productive instrument**

 CCfD could be an ambiguous policy signal and represent significant costs for the EU. Also, being a regulatory tool, its contractual features within the EU-ETS framework could create a specific type of “self-regulatory capture”.

**5.2.1. CCFD as an uncertain budgetary commitment and policy incoherence**

Carbon pricing is both central and critical for CCfD and EU climate policy. CCfD would represent a budgetary exposure for public authorities as a consequence of the insurance mechanism it entails. Both the literature and the EC have provided targeted scopes for its use that would limit this exposure, mainly related to first-of-a-kind LCH production for hard-to-abate industries. Nevertheless, the massive energy switch required by both the EU climate ambitions and the Russian gas supply cut would undoubtfully create a multiplication of projects within this limited scope. Besides, the projects count would increase quickly as investing is the very purpose of this instrument. Both elements would mechanically and proportionally augment the public exposure, the EC mentioning that to solely decarbonize the EU primary steel production 18 to 20 billion euros will be required before 2030 (EC, 2022p, p.9) giving an OoM of the financial commitments required for the entire EU economy. Additionally, the innovative process is inherently uncertain. These projects would have therefore difficulties doing financial forecasts on their costs, most probably underestimating them, an element that could see their actual investment costs rise dramatically over time, potentially further exposing public authorities. Moreover, estimations of CCfD cost for the public budgets so far have been conducted compared to EUA price previous trend, before July 2021. Although still low compared to Germain and Lellouch (2020) carbon social value estimates, this price increase demonstrates an evolution that could render CCfD useless. Additionally, the argument of CCfD supplementing EU-ETS regulatory risk as it would be considered unstable is contradictory, to say the least. Indeed, creating a public insurance on the main EU climate policy would not prove to signal its ambitions clearly, the message sent being finally quite ambiguous. Finally, in a situation of economic recession and budget constrain, certain issues could arise. First, governments could see an opportunity in using MSR’s allowances to pay potential CCfD fees to release some budgetary pressures. This could lead to undermining the EU-ETS functioning. Second, as we have seen, EUA price formation is not linear and if CCfD financial commitments would reduce “as the EU carbon price rises and low-carbon technologies become competitive without subsidy” (McWilliam & Zachmann, 2021, p.1) there is no automaticity as exogenous shocks could affect the EU-ETS.

**5.2.2. A regulation puzzle, potential source of a third type of regulatory capture?**

 The implementation of CCfD could impact the regulator due to the interplay of the risk allocation, the EU-ETS’s functioning, and EUA price formation. To foster certainty within the carbon price, the regulator would be incentivized by the contract to ensure its application at the closest price possible to the strike price. Indeed, if the execution price is be too low, the government would have to assume the costs. Conversely, an execution too high would expose agents to costs that could potentially jeopardize the funded projects, which also goes against the government’s interest as its first goal is environmental efficiency. Therefore, the more exposed the public authority would be to shocks affecting the carbon market through CCfD, the less it would be incentivized to push the carbon price higher. If they are presented as a contractual mechanism being proportionate and balanced, CCfD are most surely one-sided due to the double role of the regulator as both party to the contract and the main driver of its pivotal element: EUA price. In this sense, CCfD would act as a sort of regulatory triple bind similar to the pressure described by Bateson (1956) for schizophrenia between:

* + a voluntary chosen and weakened market-based instrument aiming at climate purposes
	+ a required technological innovation necessary to ensure economic growth together with reaching PA climate targets
	+ an indispensable carbon-intensive industry seeking jointly rents and a transition model partly funded by the government

At the extreme, due to an adverse convergence of factors, this could deter the EC to enact policies that would increase the EUA price as its financial exposure would simultaneously increase up to the point of becoming uncertain or unbearable. This confinement of the regulator within contradictory objectives could foster regulatory immobility and carbon lock-in. The carbon-intensive industries could have an interest in the realization of such a scenario, not as insurance on EUA volatility but as an insurance on the limitation or impossibility for the regulator to further increase EUA price through regulatory actions. Next to financial and cultural regulatory captures (Carpenter & Moss, 2013), this dynamic could be described as “self-imposed contractual capture” resulting from different regulation domains’ conflictual goals and under the influence of carbon-intensive industries.

Some elements already mentioned seem to support this idea as do the following ones. First, energy-intensive industries or sectors using fossil fuels as inputs for production could be affected by stranded assets as a result of the low-carbon transition. Not being able to adapt, they could not be recouped or not maximize their expected profits. As an illustration of how the industry reacted to the CCfD announcement, the European aluminum industry published recommendations in May 2022. It advocates for CCfD to cover the full differential cost between low-carbon and conventional technologies arguing that carbon costs do not always account for the alternative development costs, thus not guaranteeing commercial viability (European Aluminium, 2022). The risk covered would be much different in nature and exceed the sole EUA price volatility. Second, the language used by, and obvious contradictions of, the EC (2022f) illustrate this idea. Indeed, conceptualized as a framework to ensure market competition and adherence to the EU competition law, point 121 evokes CCfD in simple descriptive terms. However, point 123 by stating that “beneficiaries should remain exposed to price variation and market risk, unless this undermines the attainment of the objective of the aid” seems to directly contradict both its economic and legal rationale by creating a tailor-made exception. The EC recommendations appear all the more surprising and ambiguous with the objectives it set both socially and for itself. This idea of a contractual capture would nevertheless require further investigations to both assess its validity and potential applicability scope.

**5.3. Alternative policies**

 To ensure both economic and environmental efficiency, alternative policies are possible, first based on the EU-ETS, and second on energy-sufficiency planification.

**5.3.1. The carbon price as an alternative?**

Despite clear influences on its design, the EU-ETS has been able to evolve through reforming including increasingly more sectors and activities. Directive 2008/101/EC (EC, 2008) and Directive 2009/29/EC (EC, 2009) extended its scope to new sectors and the latter including new GHGs (N2O and PFCs). Current EU-ETS negotiations focus on fading out free allocations and extending further the EU-ETS scope. Further, the CBAM is a complementary policy that theoretically should both maintain the incentive for activities to remain in the EU and reinforce it through standards implementation at the EU’s borders. Still under negotiation at the EU level to come into effect in 2026, the last conversations have seen the inclusion of all EU-ETS sectors and hydrogen to ensure its compliance with the last political orientation and the EU environmental commitments. Indeed, to ensure the carbon footprint of future hydrogen imports, a certification system is required that would guarantee the low-carbon energy used for its production (IRENA, 2022a). This standard will allow avoid competition distortions after the implementation of the CBAM with countries not having the same requirements. The EU-ETS has proven its ability to be reformed and operationalized.

The argument of first-of-a-kind installations facing “higher operation and investment costs than conventional carbon-intensive processes” (Richstein & Neuhoff, 2022, p.1) is recurring. Nonetheless, this is due to their very nature, both innovative and low-carbon based, thus intrinsically more expensive than carbon-based options. This is the very issue that the EU-ETS aims at resolving by pricing carbon. Therefore, a better adjustment of this regulatory framework through a more stringent policy responds to this argument. Indeed, instating a price floor would definitively strengthen financial certainty for innovative projects and remove the need for insurance, as mentioned for the thermal pyrolysis of methane in section 2. If not solving the volatility issue completely, a clear signal rending impossible EUA price drop below a certain limit allows to stabilize it and has proven to be more effective and efficient in reducing transaction costs in other ETSs (Borghesi et al. 2016). Even Richstein and Neuhoff (2022) who argue for the implementation of CCfD recognize that “with an increasing carbon price floor, more certain revenue is available to serve debt […] more debt can be raised to finance the investment” (p.4). Their conclusion regarding the feasibility and credibility of such a policy as perceived as unstable, “while contracts are legally enforceable,” is refuted by the EUA price evolution since last year. Besides, any distortions created, and innovation support could be financed through this policy as the IF financial capacities are “around EUR 22.5 billion in the period 2020-2030 (assuming a carbon price of EUR 50/tonne) coming from the monetisation of ETS allowances.” (EC, 2021d, p.25) Since then, the EUA price has nearly doubled, and the sectors covered by the EU-ETS could be vastly extended providing more capital to the IF which could support huge LCH innovations for instance against tangible counterparts such as returns from projects and/or technologies.

A stronger argument regarding policy hesitation could be made regarding the ability of EUA price increase to stimulate inflation, which is a politically sensitive topic. By implying more costs to the sectors included under the EU-ETS, particularly basic materials as being the more polluting ones and then supplying the rest of the economy, this mechanically generates inflation downstream of the supply chains. This could lead policymakers to “intervene if they become concerned that the carbon price has societal/political effects that are too damaging” (McWilliam & Zachmann, 2021, p.5) If this evolution needs careful consideration and balance with other elements of public policy, it is the aim of the EU-ETS since its inception: increasing costs for polluting technologies to foster technological change. The implications on the overall EU economy prices over the next decades of a more stringent carbon price policy should probably be evaluated to determine where it would be more efficient to act, for all four efficiencies including the environmental one.

Finally, multiple studies note problems in data acquisition, access, and time lag urging for improvements so that more precise evaluations could be conducted (e.g., Teixidó et al., 2019). Nonetheless, it is clear that “neither carbon pricing nor a binding climate treaty are viable strategies to stabilize the planet’s climate. Both proposals reshape incentives to pollute” (Mildenberger, 2020, p.236) or “optimal levels of pollution” (Faure & Partain, 2019, p.28), which are environmental nonsense.

**5.3.2. Energy and climate change understanding for an immediate environmental response: energy sufficiency planification**

Energy systems have never experienced a transformation comparable to the one they are facing now. Additivity characterized energy systems for two centuries (Fressoz & Locher, 2020) explaining why the global share of renewables is still at 80% today as it was in 1990, even though energy production, consumption, and renewables absolute volume have drastically increased since then. If this transformation process is widely referred to as energy transition, it corresponds to a substitution: the one to replace fossil fuels with other energy sources. This process entails GHGE and further environmental damages as it shifts the productive pressure from the wells to other spaces like mines.

 To bring a solution to climate change, which is still heavily fueled by GHGE (Kühne et al., 2022), a paradigmatic shift is required. Strong sustainability must be incorporated at all levels. Energy is not produced but extracted[[6]](#footnote-6), and climate change brings risks that will eventually turn into dangers. The vision of “unlimited” natural capacities (as for CCS: UNECE, 2021, p.6) allowing unlimited productive growth, needs to be revised so that we pass from a GND-centric to a carbon-centric policy paradigm.

Furthermore, the distributional effects are not neutral. Understanding that “the economic inequality associated with historical disparities in energy consumption” (Diffenbaugh et al., 2019) will further deepen since “the intersection of inequality and poverty presents significant adaptation limits, resulting in residual impacts for vulnerable groups” (IPCC, 2022a, Chapter 1, p.63) and that “inequality fuels climate change” (Green & Healy, 2022) is in that sense key. “We must move away from a focus on economic efficiency toward a focus on the distribution of political power” (Mildenberger, 2020, p.236).

In this way, the RepowerEU (EC, 2022b) plan includes an “energy savings” part, which the EC qualifies as “vital” to reducing the EU’s energy dependency. If this seems to go in the right direction, it is nevertheless based on “energy efficiency policies” and “voluntary choices,” policy itself based on strong geopolitical constrain. If “savings are the quickest and cheapest way to address the current energy crisis” (Ibid., p.3), an energy-sufficiency planification, as recommended by the IPCC, could be the most efficient one in the long run.

**Conclusion**

 LCH presents issues that could badly hamper its environmental efficiency. Neglecting the technological neutrality principle, the EC is willing to implement CCfD for LCH. This would also hamper the overall dynamic efficiency. It also presents the possibility of locking the regulator into a dilemma regarding its climate policies. Furthermore, some risks related to financial commitments have also been identified. All these risks could undermine badly the EU-ETS functioning, which appears to have been stabilized over the last years. Betting on this technology choice, CCfD would fail to support the EU energy and climate ambitions, independently of its efficiency. EU-ETS price floor, public/private mutually beneficial innovation supports, and energy-sufficiency planification could prove to be more economically and environmentally efficient.

**Bibliography**

Akerboom, S., Waldmann, S., Mukherjee, A., Agaton, C., Sanders M., & Kramer, G.J. (2021). Different this Time? The Prospects of CCS in the Netherlands in the 2020s. *Frontiers in Energy Research*, *9*, Article 644796. [Link](https://doi.org/10.3389/fenrg.2021.644796) (accessed on May 15th 2022)

Anderson, K., & Broderick, J. (2017). *Natural Gas and Climate Change*. University of Manchester. [Link](https://www.research.manchester.ac.uk/portal/files/60994617/Natural_Gas_and_Climate_Change_Anderson_Broderick_FOR_DISTRIBUTION.pdf) (accessed on April 4th 2022)

Andersson, J., & Grönkvist, S. (2019). Large-Scale Storage of Hydrogen. *International Journal of Hydrogen Energy*, *44*(23), 11901-11919. [Link](https://doi.org/10.1016/j.ijhydene.2019.03.063) (accessed on April 4th 2022)

Babiker, M., Reilly, J., & Viguier, L. (2004). Is International Emissions Trading Always Beneficial?. *The Energy Journal*, *25*(2), 33-56. [Link](http://dx.doi.org/10.2307/41323030) (accessed on May 15th 2022)

Baldwin, R. (2008). Regulation Lite: The Rise of Emissions Trading. *Regulation & Governance*, *2*(2), 193-215. [Link](https://doi.org/10.1111/j.1748-5991.2008.00033.x) (accessed on March 15th 2022)

Bateson, G., Jackson, D. D., Haley, J., & Weakland, J. (1956). Toward a Theory of Schizophrenia. *Behavioral Science*, *1*(4), 251-254. [Link](https://doi.org/10.1002/bs.3830010402)

Bayer, P., & Aklin, M. (2020). The European Union Emissions Trading System Reduced CO2 Emissions Despite Low Prices. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(16), 8804-8812. [Link](https://doi.org/10.1073/pnas.1918128117)

Bel, G., & Joseph, S. (2015). Emission Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis. *Energy Economics*, *49*, 531-539. [Link](https://doi.org/10.1016/j.eneco.2015.03.014)

Borghesi, S., & Montini, M. (2016). The Best (and Worst) of GHG Emission Trading Systems: Comparing the EU ETS with Its Followers. *Frontiers in Energy Research*, *4*(27). [Link](https://doi.org/10.3389/fenrg.2016.00027)

Calel, R. (2018). Adopt or Innovate: Understanding Technological Responses to Cap-and-Trade. CESifo Working Paper 6847. [Link](https://dx.doi.org/10.2139/ssrn.3138407)

Carpenter, D., & Moss, D. A. (2013). *Preventing Regulatory Capture, Special Interest Influence and How to Limit It*. Cambridge University Press.

CFMP. (2020). *Carbon Contracts for Differences: Their Role in European Industrial Decarbonization*. [Link](https://climatestrategies.org/wp-content/uploads/2021/03/Carbon-Contracts_CFMP-Policy-Brief-2020.pdf)

Chiappinelli, O., & Neuhoff, K. (2020). *Time-Consistent Carbon Pricing: The Role of Carbon Contracts for Differences*. DIW Discussion Papers Nº 1859. [Link](https://www.diw.de/de/diw_01.c.758552.de/publikationen/diskussionspapiere/2020_1859/time-consistent_carbon_pricing__the_role_of_carbon_contracts_for_differences.html)

Cludius, J. (2018). Winners and Losers of EU Emissions Trading: Insights From the EUTL Transfer Dataset. *Economics of Energy and Environmental Policy*, *7*(2), 93-110. [Link](http://dx.doi.org/10.5547/2160-5890.7.2.jclu)

Coase, R. H. (1960). The problem of Social Cost. In *Classic papers in natural resource economics*, Palgrave Macmillan London, 87-137.

Convery, F. (2009). Origins and Development of the EU ETS. *Environmental and Resource Economics*, *43*, 391-412. [Link](https://link.springer.com/article/10.1007/s10640-009-9275-7)

Crocker, T. D. (1968). Some Economics of Air Pollution Control. *Natural Resources Journal*, *8*(2), 236-258. [Link](https://core.ac.uk/download/pdf/151602658.pdf)

Dai, X., Xiao, L., Wang, Q., & Dhesic, G. (2021). Multiscale Interplay of Higher-Order Moments Between the Carbon and Energy Markets During Phase III of the EU ETS. *Energy Policy*, *156*, Article 112428. [Link](https://doi.org/10.1016/j.enpol.2021.112428)

Dales, J. (1968). *Pollution, Property and Prices: An Essay in Policy*. University of Toronto Press, 1968.

De Perthuis, C., & Trotignon, R. (2014). Governance of CO2 Markets: Lesson from the EU ETS. *Energy Policy*, *75*, 100-106. [Link](https://doi.org/10.1016/j.enpol.2014.05.033)

Den Hertog, J. A. (2010). Review of Economic Theories of Regulation. Tjalling C. Koopmans Research Institute, Discussion Paper Series N°10-18. [Link](https://www.uu.nl/sites/default/files/rebo_use_dp_2010_10-18.pdf)

DERA. (2021). *Mineralische Rohstoffe für die Wasserelektrolyse*. Bundesanstalt für Geowissenschaften und Rohstoffe

Derwent, R., Simmonds, P., O’Doherty, S., Manning, A., Collins, W., Johnson, C., Sanderson, M., & Stevenson, D., (2006). Global Environmental Impacts of the Hydrogen Economy. *International Journal of Nuclear Hydrogen Production and Application*, *1*(1), 57-67. [Link](https://doi.org/10.1504/ijnhpa.2006.009869) (accessed on April 4th 2022)

Deshaies, M. (2020). Problèmes géographiques des transitions énergétiques : quelles perspectives pour l’évolution du système énergétique ?. *Mondes en développement*, 192, 25-44. [Link](https://doi.org/10.3917/med.192.0025) (accessed on May 8th 2022)

Diffenbaugh, N. S., & Burke, M. (2019). Global Warming has Increased Global Economic Inequality. *Proceedings of the National Academy of Sciences*, *116*(20), 9808-9813. [Link](https://doi.org/10.1073/pnas.1816020116)

EBRD. (2020). *Methodology for the Economic Assessment of EBRD Projects with High Greenhouse Gas Emissions – Technical note*. [Link](https://www.ebrd.com/news/publications/institutional-documents/methodology-for-the-economic-assessment-of-ebrd-projects-with-high-greenhouse-gasemissions.html)

EC, n.d. Market Stability Reserve. [Link](https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/market-stability-reserve_en#:~:text=The%20reserve%3A,of%20allowances%20to%20be%20auctioned.)

EC, n.d./b. EU Emissions Trading System (EU ETS). [Link](https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en)

EC. (2008). *Directive 2008/101/EC Amending Directive 2003/87/EC so as to Include Aviation Activities in the Scheme for Greenhouse Gas Emission Allowance Trading within the Community*. Official Journal of the European Union. [Link](http://data.europa.eu/eli/dir/2008/101/oj)

EC. (2009). *Directive 2009/29/EC Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community*. Official Journal of the European Union. [Link](http://data.europa.eu/eli/dir/2009/29/oj)

EC. (2011). *Commission Regulation (EU) No 1210/2011 of 23 November 2011 amending Regulation (EU) No 1031/2010 in particular to determine the volume of greenhouse gas emission allowances to be auctioned prior to 2013.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011R1210)

EC. (2012). *Report from the Commission to the European Parliament and the Council - The State of the European Carbon Market in 2012*. COM(2012) 652 final. Official Journal of the European Union. [Link](https://ec.europa.eu/clima/system/files/2016-11/com_2012_652_en.pdf)

EC. (2013). *Commission Regulation (EU) No 389/2013 of 2 May 2013 establishing a Union Registry pursuant to Directive 2003/87/EC of the European Parliament and of the Council, Decisions No 280/2004/EC and No 406/2009/EC of the European Parliament and of the Council and repealing Commission Regulations (EU) No 920/2010 and No 1193/2011*. Official Journal of the European Union. [Link](http://data.europa.eu/eli/reg/2013/389/oj)

EC. (2014). *Commission Regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2013-20.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.056.01.0011.01.ENG)

EC. (2019a). *Fossil CO2 and GHG emissions of all world countries : 2019 report*. Joint Research Centre, Publications Office. [Link](https://data.europa.eu/doi/10.2760/687800)

EC. (2019b). *Communication From the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - The European Green Deal.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN)

EC. (2019c)*. Commission Delegated Regulation (EU) 2019/856 of 26 February 2019 supplementing Directive 2003/87/EC of the European Parliament and of the Council with regard to the operation of the Innovation Fund.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32019R0856)

EC. (2021a). *Communication From the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - 'Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550)

EC. (2021b). *Commission Delegated Regulation (EU) 2021/1204 of 10 May 2021 amending Delegated Regulation (EU) 2019/856 as regards the application and selection procedures under the Innovation Fund*. Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2021.261.01.0004.01.ENG)

EC. (2021c). *Commission Staff Working Document Impact Assessment Report Accompanying the Document Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757*. Official Journal of the European Union, SWD/2021/601 final, document 4. [Link](https://eur-lex.europa.eu/resource.html?uri=cellar:7b89687a-eec6-11eb-a71c-01aa75ed71a1.0001.01/DOC_4&format=PDF)

EC. (2021d). *Commission Staff Working Document Impact Assessment Report Accompanying the Document Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757*. Official Journal of the European Union, SWD/2021/601 final, document 1. [Link](https://eur-lex.europa.eu/resource.html?uri=cellar:7b89687a-eec6-11eb-a71c-01aa75ed71a1.0001.01/DOC_1&format=PDF)

EC. (2022a). *State Aid: Commission approves up to €5.4 billion of public support by fifteen Member States for an Important Project of Common European Interest in the hydrogen technology value chain*. [Link](https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4544) (accessed on July 25th 2022)

EC. (2022b). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - REPowerEU Plan*. COM(18th May 2022) 230 final. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN)

EC. (2022c). *Innovation Fund - Key statistics from the first Call for Large-Scale Projects.* [Link](https://ec.europa.eu/clima/system/files/2022-01/policy_innovation-fund_lsc_statistics_en_0.pdf)

EC. (2022d). *EU Experts Model Contract for Experts Funding & Tenders Portal Expert Database*. Version 2.1 of January 11th 2022. [Link](https://ec.europa.eu/research/participants/data/ref/h2020/experts_manual/h2020-experts-mono-contract_en.pdf#page=45) (accessed on June 6th 2022)

EC. (2022e). *Innovation Fund Expert Group 12 July 2022*, meeting presentation. [Link](https://ec.europa.eu/clima/system/files/2022-07/20221712_presentation_1_en_0.pdf) (accessed on July 29th 2022)

EC. (2022f). Communication From the Commission - Guidelines on State aid for climate, environmental protection and energy 2022, [2022/C 80/01]. Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2022.080.01.0001.01.ENG&toc=OJ%3AC%3A2022%3A080%3ATOC)

EEA. (2022). *The EU Emissions Trading System in 2021: trends and projections*. [Link](https://www.eea.europa.eu/downloads/aec20c02255b4ea58e9bd45a94cb45ea/1644510582/the-eu-emissions-trading-system.pdf)

Egenhofer, C., Marcu, A., & Georgiev, A. (2012). *Reviewing the EU ETS Review?*. Center for European Policy Studies Task Force Reports. [Link](https://ssrn.com/abstract%3D2179814)

Eichner, T., & Pethig, R. (2019). EU-type carbon regulation and the waterbed effect of green energy promotion. *Energy Economics*, *80*, 656-679 [Link](https://doi.org/10.1016/j.eneco.2019.01.019)

Ellerman, D. (2009). The EU’s Emissions Trading Scheme: a Prototype Global System?. In: Post-Kyoto International Climate Policy, eds J.Aldy and R. N.Stavins, Cambridge University Press, 88-118. [Link](https://doi.org/10.1017/CBO9780511813207.004)

Engstrom, F. (2013). Corralling Capture. *Harvard Journal of Law and Public Policy*, *36*, 31-39. [Link](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2341810)

EPC. (2003). *Directive 2003/87/EC Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and amending Council Directive 96/61/EC*. Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003L0087)

EPC. (2009). *Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community*. Official Journal of the European Union. [Link](https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF)

EPC. (2015). *Decision (EU) 2015/1814 of the European Parliament and of the Council of 6 October 2015 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and amending Directive 2003/87/EC.* Official Journal of the European Union. [Link](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2015.264.01.0001.01.ENG)

EPC. (2018). *Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814.* Official Journal of the European Union. [Link](http://data.europa.eu/eli/dir/2018/410/oj)

European Aluminium. (2022). *Reconciling Growth and Decarbonisation Amidst the Energy Crisis, European Aluminium Reaction to the RePowerEU Plan*. [Link](https://www.european-aluminium.eu/media/3553/2022-05-20-european-aluminium-response-to-repowereu.pdf)

Eurostat. (2020). *Energy, Transport and Environment Statistics Edition 2020*. [Link](https://doi.org/10.2785/522192)

Faure, M.G., & Partain, R.A. (2019). *Environmental Law and Economics, Theory and Practice*. Cambridge University Press.

Fields, M., & Lindequist, D. (2022). Global Spillovers of US Climate Policy Risk: Evidence from EU Carbon Emissions Futures. [Link](https://dx.doi.org/10.2139/ssrn.4170198)

Fischer, C., & Newell, R.G. (2008). Environmental and Technology Policies for Climate Mitigation. *Journal of Environmental Economics and Management*, *55*, 142-162. [Link](https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/6623/FischerNewellJEEM.pdf?sequence=1&isAllowed=y) (accessed on July 2nd 2022)

Forster, P. M., Forster, H. I., Evans, M. J., Gidden, M.J., Jones, C. D., Keller, C. A., Lamboll, R. D., Le Quéré, C., Rogelj, J., Rosen, D., Schleussner, C-F., Richardson, T. B., Smith, C. J., & Turnock, S. T. (2020). Current and Future Global Climate Impacts Resulting from COVID-19, *Nature Climate Change*, *10*, 913-919. [Link](https://doi.org/10.1038/s41558-020-0883-0)

Fressoz, J-B., & Locher, F. (2020). *Les Révoltes du ciel, Une histoire du changement climatique XVe-XXe siècle*. Seuil, Paris.

Frunza, M., Guegan, D., & Thiebaut, F. (2011). Missing Trader Fraud on the Emissions Market. Journal of Financial Crime, 18(2), 183-194. [Link](https://doi.org/10.1108/13590791111127750)

Fuchs, D., & Feldhoff, B. (2016). Passing the Scepter, not the Buck: Long Arms in EU Climate Politics. *Journal of Sustainable Development*, *9*(6), 58-74. [Link](https://doi.org/10.5539/jsd.v9n6p58)

Germain, J-M., & Lellouch, T. (2020). The Social Cost of Global Warming and Sustainability Indicators: Lessons from an Application to France. [*Economie et Statistique*](https://ideas.repec.org/s/nse/ecosta.html), Institut National de la Statistique et des Études Économiques, *517-518*(5), 81-102. [Link](https://www.insee.fr/en/statistiques/fichier/4770154/06-ES_517-518-519_Germain-Lellouch_ENWeb.pdf)

Global CCS Institute. (2021). *Global Status of CCS 2021*. [Link](https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf)

Green, F. & Healy, N. (2022). How Inequality Fuels Climate Change: The Climate Case for a Green New Deal. *One Earth*, *5*(6), 635-649. [Link](https://doi.org/10.1016/j.oneear.2022.05.005)

Green, J. F. (2021). Does Carbon Pricing Reduce Emissions? A Review of Ex-Post Analyses. *Environmental Research Letters*, *16*(4), Article 043004. [Link](https://ui.adsabs.harvard.edu/link_gateway/2021ERL....16d3004G/doi%3A10.1088/1748-9326/abdae9)

Gronwald, M., & Hintermann, B. (2015). *Evaluating Emission Trading as a Policy Instrument: Evaluation and Prospects*. Massachusetts Institute of Technology.

Helm, D., & Hepburn, C. (2005). *Carbon Contracts and Energy Policy: an Outline Proposal*. Oxford University Department of Economics. Discussion Paper. [Link](https://www.researchgate.net/publication/228449831_Carbon_contracts_and_energy_policy_An_outline_proposal)

Hicks, J. R. (1932). *The Theory of Wages*. Macmillan, London

Hydrogen Europe. (2021). Open Letter Raising Concern on the Delegated Act on Art 27.3. [Link](https://hydrogeneurope.eu/wp-content/uploads/2021/12/2021.12.08_Hydrogen-Industry-Letter_DA-on-additionality_final.pdf)

IEA. (2018). *Hydrogen from Biomass Gasification*. [Link](https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf)

IEA. (2019). *The Future of Hydrogen, Seizing Today’s Opportunities*. [Link](https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf)

IPCC. (2021). Annex VII: Glossary in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou (eds.)]. Cambridge University Press. In Press. [Link](https://www.ipcc.ch/report/ar6/wg1/)

IPCC. (2022a). *Climate Change 2022: Impacts, Adaptations and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Link](https://www.ipcc.ch/report/ar6/wg2/)

IPCC. (2022b). The Evidence is Clear: the Time for Action is Now. We can halve emissions by 2030. *IPCC press release* [2022/15/PR]. [Link](https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/)

IRENA. (2022a). *Decarbonising End-Use Sectors: Green Hydrogen Certification*. [Link](https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_Green_Hydrogen_Certification_Brief_2022.pdf)

IRENA. (2022b). *Geopolitics of the Energy Transformation - The Hydrogen Factor*. [Link](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf)

Kakoulaki, G., Kougias I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green Hydrogen in Europe - A regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables. *Energy Conversion and Management*, *228*, Article 113649. [Link](https://doi.org/10.1016/j.enconman.2020.113649)

Kaplow, L., & Shavell, S. (2002). On the Superiority of Corrective Taxes to Quantity Regulation. *American Law and Economics Review*, *4*(1), 1-17. [Link](https://www.jstor.org/stable/42705401)

Kemp, R. (2010). Eco-Innovation: Definition, Measurement and Open Research Issues. *Economia Politica*, *27*(3), 397-420. [Link](https://www.rivisteweb.it/doi/10.1428/33131)

Köberle, A.C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., Tavoni, M., & Rogelj, J. (2021). The Cost of Mitigation Revisited. *Nature Climate Change*, *11*, 1035-1045. [Link](https://doi.org/10.1038/s41558-021-01203-6)

Koch, N., Fuss, S., Grojean, G., & Edenhofer, G. (2014). Causes of the EU ETS Price Drop: Recession, CDM, Renewable Policies or A Bit of Everything? - New Evidence, *Energy Policy*, *73*, p.676-685. [Link](https://doi.org/10.1016/j.enpol.2014.06.024)

Kühne, K., Bartsch, N., Tate, R.D., Higson, J., & Habet, A. (2022). “Carbon Bombs“ – Mapping Key Fossil Fuel Projects. *Energy Policy*, *166*, Article 112950. [Link](https://doi.org/10.1016/j.enpol.2022.112950)

Landis, F., Fredriksson, G., & Rausch, S. (2021). Between- and Within-Country Distributional Impacts from Harmonizing Carbon Prices in the EU. *Energy Economics*, *103*, Article 105585. [Link](https://doi.org/10.1016/j.eneco.2021.105585)

Lovcha, Y., P-L, A., & Sikora, I. (2022). The Determinants of CO2 Prices in the EU Emission Trading System. *Applied Energy*, *305*, Article 117903. [Link](https://doi.org/10.1016/j.apenergy.2021.117903)

Lütkehus, R. (2022). Hydrogen import is the Most Cost-Effective Solution for the EU, *Energate Messenger*. [Link](https://www.energate-messenger.com/news/221991/hydrogen-import-is-the-most-cost-effective-solution-for-the-eu)

Marcantonini, C., [Teixido-Figueras, J.](https://cadmus.eui.eu/browse?type=author&value=TEIXIDO-FIGUERAS,%20Jordi), [Verde, S.F.](https://cadmus.eui.eu/browse?type=author&value=VERDE,%20Stefano%20F.), & [Labandeira, X.](https://cadmus.eui.eu/browse?type=author&value=LABANDEIRA,%20Xavier) (2017). Low-Carbon Innovation and Investment in the EU ETS. Policy Briefs, 2017/22, Florence School of Regulation. [Link](http://hdl.handle.net/1814/47525)

Martin, R., Muûls, M., & Wagner, U. J. (2016). The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What is the Evidence After Ten Years?. *Review of environmental economics and policy*, *10*(1), 129-148. [Link](https://core.ac.uk/download/pdf/249953868.pdf)

Maskin, E., & Tirole, J. (2004). The Politician and the Judge: Accountability in Government. *American Economic Review*, *94*(4), 1034-1054. [Link](https://www.aeaweb.org/articles?id=10.1257/0002828042002606)

McWilliam, B., & Zachmann, G. (2021). Commercialisation Contracts: European Support for Low-Carbon Technology Deployment. Policy Contribution, *15*, Bruegel. [Link](https://www.bruegel.org/policy-brief/commercialisation-contracts-european-support-low-carbon-technology-deployment)

Mildenberger, M. (2020). *Carbon captured : how business and labor control climate politics*. The MIT Press.

Nash, J. R. (2000). Too Much Market: Conflict between Tradable Pollution Allowances and the Polluter Pays Principle. *The Harvard Environmental Law Review*, 24(2), 465-535. [Link](https://www.researchgate.net/publication/291559588_Too_Much_Market_Conflict_Between_Tradable_Pollution_Allowances_and_the_%27Polluter_Pays%27_Principle)

Noussan, M., Raimondi, P.P., Scita, R., & Hafner, M. (2021). The Role of Green and Blue Hydrogen in the Energy Transition - A Technological and Geopolitical Perspective. *Sustainability*, *13*(1), Article 298. [Link](https://doi.org/10.3390/su13010298)

Nuñez-Jimenez, A., & De Blasio, N. (2022). The Future of Renewable Hydrogen in the European Union Market and Geopolitical Implications. Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School. [Link](https://www.belfercenter.org/publication/future-renewable-hydrogen-european-union-market-and-geopolitical-implications-0)

Ocko, I. B., & Hamburg, S. P. (2022). Climate Consequences of Hydrogen Emissions. *Atmospheric Chemistery and Physics*, *22*, 9349-9368. [Link](https://doi.org/10.5194/acp-22-9349-2022)

OECD. (2021). *OECD Economic Surveys: European Union 2021*. [Link](https://doi.org/10.1787/a77ab220-en)

OECD/IEA. (2016). *20 Years of Carbon Capture and Storage - Accelerating Future Deployment*. [Link](https://iea.blob.core.windows.net/assets/24c3d26b-aa44-4b54-b9c0-5201d4d86a04/20YearsofCarbonCaptureandStorage_WEB.pdf)

Ohlig, K., & Decker, L. (2014). The Latest Developments and Outlook for Hydrogen Liquefaction Technology. AIP Conference Proceedings, *1573*(1), Article 1311. [Link](https://aip.scitation.org/doi/abs/10.1063/1.4860858)

Parkinson, B., Tabatabaei, M., Upham, D.C., Ballinger, B., Greig, C., Smart, S., & McFarland, E. (2018). Hydrogen Production using Methane: Techno-Economics of Decarbonizing Fuels and Chemicals. *International Journal of Hydrogen Energy*, *43*(5), 2540-2555. [Link](https://doi.org/10.1016/j.ijhydene.2017.12.081)

Pflugmann, F., & De Blasio, N. (2020). *Geopolitical and Market Implications of Renewable Hydrogen New Dependencies in a Low-Carbon Energy World*. Harvard Kennedy School. [Link](https://www.belfercenter.org/sites/default/files/files/publication/Geopolitical%20and%20Market%20Implications%20of%20Renewable%20Hydrogen.pdf)

Pigou, A.C. (1920). *The Economics of Welfare*. London Macmillan & Co.

Popp, D. (2019). Environmental Policy and Innovation: a Decade of Research. *International Review of Environmental and Resource Economics*, *13*(3–4), 265-337. [Link](http://dx.doi.org/10.1561/101.00000111)

Preuster, P., Alezseev, A., & Wassercheid, P. (2017). Hydrogen Storage Technologies for Future Energy Systems. *Annual Review of Chemical and Biomolecular Engineering*, *8*(1), 445-471. [Link](https://doi.org/10.1146/annurev-chembioeng-060816-101334)

Prinzhofer, A., Cissé, C.S.T., & Diallo, A.B. (2018). Discovery of a Large Accumulation of Natural Hydrogen in Bourakebougou (Mali). *International Journal of Hydrogen Energy*, *43*(42), 19315-19326. [Link](https://doi.org/10.1016/j.ijhydene.2018.08.193)

Quirion, P. (2021). Tradable Instruments to Fight Climate Change: A Disappointing Outcome. *WIREs Climate Change*, *12*(3). [Link](https://doi.org/10.1002/wcc.705)

Requate, T. & Unold, W. (2003). Environmental Policy Incentives to Adopt Advanced Abatement Technology: Will the True Ranking Please Stand up?. *European Economic Review*, *47*(1), 125-146. [Link](https://www.sciencedirect.com/science/article/abs/pii/S0014292102001885?via%3Dihub)

Richstein, J. C., & Neuhoff, K. (2022). Carbon Contracts-for-Difference: How to De-Risk Innovative Investments for a Low-Carbon Industry?. *IScience*, *25*, Article 104700. [Link](https://doi.org/10.1016/j.isci.2022.104700)

Sartor, O., & Bataille, C. (2019). *Decarbonising Basic Materials in Europe: How Carbon Contracts-for-Difference Could Help Bring Breakthrough Technologies to Market*. IDDRI / Institute for Sustainable Development and International Relations, study 6, SciencesPo. [Link](https://www.iddri.org/en/publications-and-events/study/decarbonising-basic-materials-europe)

Sato, M., Rafaty, R., Calel, R., & Grubb, M. (2022). Allocation, allocation, allocation! The Political Economy of the Development of the European Union Emissions Trading System. *WIREs Climate Change*. [Link](https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wcc.796)

Sijm, J. (2005). The interaction between the EU Emissions Trading Scheme and national energy policies. *Climate Policy*, *5*(1), 79-96. [Link](http://dx.doi.org/10.1080/14693062.2005.9685542)

Skjærseth, J. B., & Wettestad, J. (2009). The Origin, Evolution and Consequences of the EU Emissions Trading System. [*Global Environmental Politics*](https://www.researchgate.net/journal/Global-Environmental-Politics-1536-0091),*9*(2), 101-122. [Link](http://dx.doi.org/10.1162/glep.2009.9.2.101)

Sorrell, S., & Skea J. (1999). *Pollution for sale: emissions trading and joint implementation*. Edward Elgar, Northampton

Stigler, G. J. (1971). The Theory of Economic Regulation. *The Bell Journal of Economics and Management Science*, *2*(1), 3-21. [Link](https://doi.org/10.2307/3003160)

Teixidó, J., Verde, S. F., & Nicolli, F. (2019). The Impact of the EU Emissions Trading System on Low-Carbon Technological Change: The Empirical Evidence. *Ecological economics*, *164*, Article 106347. [Link](https://doi.org/10.1016/j.ecolecon.2019.06.002)

Thaler, P., & Hofmann, B. (2022). The Impossible Energy Trinity: Energy Security, Sustainability, and Sovereignty in Cross-Border Electricity Systems. Political Geography, *94*, Article 102579. [Link](https://www.sciencedirect.com/science/article/pii/S0962629821002390#!)

The Royal Society. (2018). *Options for Producing Low-Carbon Hydrogen at Scale*. [Link](https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf)

UNECE. (2021). *Technology Brief - Carbon Capture, Use and Storage*. [Link](https://unece.org/sites/default/files/2021-03/CCUS%20brochure_EN_final.pdf) (accessed on April 4th 2022)

UNEP. (2020). *Emissions Gap Report 2020*. [Link](https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34426/EGR20.pdf?sequence=1&isAllowed=y)

UN. (2015, December 12). *Paris Agreement*. [Link](https://unfccc.int/sites/default/files/english_paris_agreement.pdf) (accessed on April 4th 2022)

Van de Graaf, T. (2021). The Next Prize: Geopolitical Stakes in the Clean Hydrogen Race. *Forum.* The Oxford Institute for Energy Studies. [Link](https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/02/THE-NEXT-PRIZE-GEOPOLITICAL-STAKES-IN-THE-CLEAN-HYDROGEN-RACE.pdf)

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W., & Lenaerts, S. (2021). Challenges in the Use of Hydrogen for Maritime Applications. *Energy & Environmental Science*, *14*(2), 815-843. [Link](https://doi.org/10.1039/D0EE01545H)

WB. (2017). *Report of the High-Level Commission on Carbon Prices*. [Link](http://hdl.handle.net/10986/32419)

Wei, Y-M., Han, R., Wang, C., Yu, B., Liang, Q-M., Yuan, X-C., Chang, J., Zhao, Q., Liao, H., Tang, B., Yan, J., Cheng, L., & Yang, Z. (2020). Self-Preservation Strategy for Approaching Global Warming Targets in the Post-Paris Agreement Era. *Nature Communications*, *11*, Article 1624. [Link](https://www.nature.com/articles/s41467-020-15453-z#:~:text=Compared%20to%20the%20current%20NDCs,6a).)

Welsby, D., Price, J., Pye, S., & Ekins, P. (2021). Unextractable Fossil Fuels in a 1.5°C

World. *Nature*, *597*, 230-234. [Link](https://www.nature.com/articles/s41586-021-03821-8) (accessed on June 17th 2022)

Wildgrube, T. (2022). *Fit for 55? An assessment of the effectiveness of the EU COM’s reform proposal for the EU ETS?*. Institute of Energy Economics at the University of Cologne (EWI), EWI Working Paper, No 22/04. [Link](https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2022/03/EWI_WP_22-04_Fit-for-55.pdf)

1. As opposed to the production of hydrogen as an industrial co-product of reactions aimed at the production of other chemical elements. [↑](#footnote-ref-1)
2. That consumes heat. [↑](#footnote-ref-2)
3. Battery in which the oxidation of hydrogen on one electrode coupled to the reduction on the other electrode of oxygen from the air allows the generation of electricity [↑](#footnote-ref-3)
4. CO2 fluid state obtained when maintained above its critical temperature and pressure. [↑](#footnote-ref-4)
5. Own translation from original French text [↑](#footnote-ref-5)
6. As per the law of conservation of energy, energy in an isolated system is constant. The transformation from one energy carrier to another implies loses. [↑](#footnote-ref-6)