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“And there's mad luck and bad luck
And what I could've had luck
And it's governed by blaggards
In the hills far away
And there's robbers and ruses
And a thousand excuses
For the hard life of Ivan MacCrae”

“The Hard Life of Ivan MacRae”- Barleyjuice

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Introduction

"Water: 35 liters, Carbon: 20 kg, Ammonia: 4 liters, Lime:1.5 kg, Phosphorus: 800 g, salt: 250g, saltpeter: 100g, Sulfer: 80g, Fluorine: 7.5 g, iron: 5.6 g, Silicon: 3g, and 15 other elements in small quantities... that's the total chemical make-up of the average adult body"

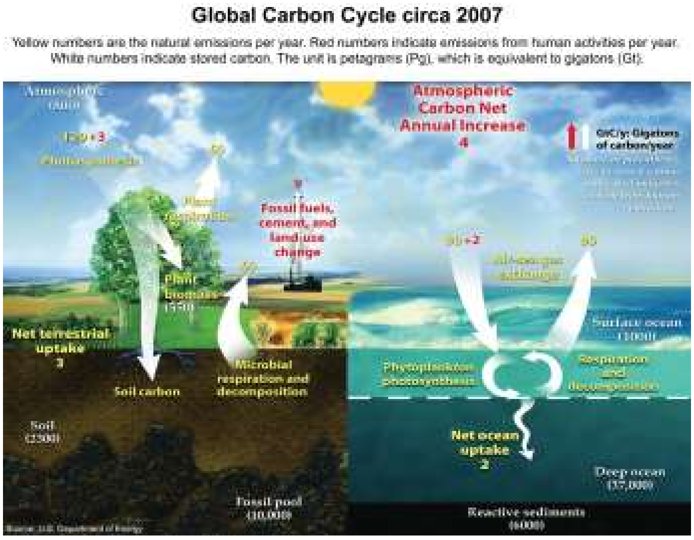
Hiromu Arakawa, Full Metal Alchemist, Vol. 1[1]

Carbon represents the backbone of life on earth. It has the almost unique ability to form long chains and stable rings with five or six members. Besides, carbon dioxide (CO_2) is unusually stable, always monomeric (it remains in a single molecule), and readily soluble in water[2] (Frieden, 1972). Considering those characteristics, carbon, together with the other five elements (i.e., Oxygen, Nitrogen, Phosphorous, and Sulphur), can be defined as one of the building blocks of living matter (Frieden, 1972). Most of the carbon in the Planet is stored in rocks, while the rest is embedded in the ocean, atmosphere, plants, soil, and fossil fuels (e.g., carbon sinks). Those sinks continuously exchange carbon in what is known as Carbon Cycles (e.g., slow and fast, see Figure 1). Carbon Cycles prevent all the carbon from being released into the atmosphere keeping temperatures relatively stable, like in a thermostat (Lacis et al., 2010). The Slow carbon cycle is responsible for temperature changes between ice ages and warmer interglacial periods. The Fast carbon cycle regards carbon exchanges among organic and inorganic matter on Earth. For instance, plants synthetise carbon dioxide to produce energy and release oxygen into the atmosphere. This multiple equilibria among the slow and fast carbon cycle keep the Planet under this thermostat can only be perturbed through changes in one sink. In the past, those cycles have only changed in response to climate change due to shifts in Earth's orbit.

[1] Although quantities may vary according to multiple factors (e.g., sex, age), Hydrogen (H) and Oxygen (O) account for 88.5% (63% and 25.5%, respectively) of the atoms in the human body. It follows Carbon (C) accounting for 9.5%, Nitrogen (N) for 1.4% plus other elements (e.g., traces elements) which account for no more than 0.7% overall (Frieden, 1972)

[2] Frieden (1972) defines water as "the solvent base of all life on the earth" and many of the compounds are essential to life on earth with respect to their response to water (e.g., solubility, capacity of carrying electricity charge in water, effects on viscosity of water).

Figure 1 Carbon Cycle



Source U.S. Department of Energy

Indeed, studies have proved that changes in the concentration of carbon dioxide are one significant factor for changes in temperature and climate change (Lacis et al., 2010). This includes the amount of CO_2 released due to human consumption and production processes. In fact, since the mid-20th century, human activities have become a significant factor triggering climate changes, as stated by IPCC (2018a). While average global temperature has increased by 0.85°C from 1880 to 2012, many regions have already experienced average temperatures above 1.5°C. On the other hand, if carbon cycles keep the earth's temperature within a specific range favouring life on earth, increasing CO_2 from exogenous sources (e.g., human activities) are factors perturbing this kind of equilibrium. In addition, according to projections, responses of some significant climate system components to anthropogenic climate change manifest over decades (IPCC, 2021). It is thus quite difficult to predict the consequences in the future of current changes in the concentration of CO_2. Besides, those regions that are foremost responsible for anthropogenic CO_2 emissions do not bear the total cost of climate change. Regions of the world more exposed or vulnerable to climate change are also less wealthy. This generates adaptation costs that might be very challenging to sustain. Recent extreme events have highlighted how climate change is now impacting those wealthier regions. Last summer, an agrometeorological station in Sicily set the provisional European record of 48.8° C in August 2021. Within July 14-15, 2021, western Germany and eastern Belgium received 100 to 150 mm of rain (the highest daily rainfall was 162.4 mm at Wipperfürth - Gardenau (Germany) over a wide area, causing flooding and landslides and 200 deaths. This demonstrates how wealthier nations are now in the position of both mitigating and adapting to climate change. On the other hand, a more environmentally and socially aligned development will be the biggest challenge for those countries in other regions showing impressive growth in their domestic production. One relevant hurdle, in economic terms, to promote mitigation and adaptation is related to the so-called *market failure* of externalities.

In this perspective, the debate at the policy level around charging a price to human-made carbon emissions represents a relevant challenge and a necessary step towards more sustainable production and consumption systems. Economists look at carbon pricing as an overarching solution to push innovation and reduce costs of the sustainability transition. Instead of direct interventions by governments setting technological standards or reduction objectives (e.g., command-and-control), carbon price could lead to the ideal level of CO_2 emissions for the environment without endangering human thriving (High-Level Commission on Carbon Pricing and Competitiveness 2018). Ideally, carbon prices could provide helpful information to producers and consumers on the cost of CO_2 emissions generated by their activities. Correct carbon pricing will provide a monetary value to all the economic and non-economic damages related to environmental emissions. In economic policy, this considerable endeavour revolves around the fundamental concepts of the carbon tax and carbon markets. Those two policy instruments are the product of two different policymaking approaches stemming from the seminal work by Arthur Pigou (1920) and Ronald Coase (1960). All the speculation around externalities for Pigou stems from divergences between marginal private and social net products. Pigou argues that self-interest behaviour by private industrialists will impede net social product to tend to a maximum. Theoretically, those divergences may even occur under simple competition conditions as under monopolistic or bilateral monopoly. In other terms, considering a transaction between two parts, the costs and benefits of that transaction may affect positively or negatively another external part. In some cases, according to Pigou, divergences arise out of the difference between ownership and tenancy of durable instruments of production. Of the same opinion was Ronald Coase in his seminal work. He reached this very same conclusion bringing case-specific examples on ownership and use of a specific resource (e.g., the environment). Attribution of property rights holds society responsible for protecting public goods (e.g., the environment) from being exploited. On the other hand, for Pigou, the difference between public and private ownership was of no practical use if a system of either taxes, grants, or subsidies would compensate for the divergences. Both those approaches entail strengths and weaknesses. Nonetheless, while monetizing the social cost of carbon is one necessary step to proceed further with the sustainability transition, the choice of a specific figure is of the utmost importance at the policy level (Pearce, 1991). Usually, the discourse around a specific monetary value to carbon aims to find the most appropriate criteria to minimize the costs to achieve a particular target (e.g., mitigation) (Pearce, 1991). Critics of the strict monetization of carbon prices tend to look at the marketplace and its ability to provide the most efficient allocation of resources. On the other hand, markets bear their issues concerning the equity and equal distribution of resources. Since no global-warming projection foresees income loss, sacrificing resources in the present will likely benefit communities more affluent than the poorest today (Pearce, 1991). In other terms, actions taken now involve consequences for future generations. Though, any form of sustainable carbon pricing should ideally conceive distributional mechanisms to (partially) cope with inequalities in the present (European Environment Agency, 2017). As already mentioned, setting a price to carbon is a necessary measure at the policy level with repercussions towards producers, consumers, and investors. The more the price mechanism reflects the social costs carbon dioxide emissions embeds, the more it provides a better signal concerning market agents' consumption, production, and investment decisions.

Regarding financing the sustainability transition, providing a comprehensive framework to investors will help shape better investment decision-making. As of now, the bulk of the issues for the sustainability transition of finance boils down to the lack of a concrete framework of definition, coupled with a lack of concrete proof of an advantage to invest in more sustainable assets (e.g., *greenium*) and the lack of a concrete mechanism for assessing risks on financial assets related to climate change. As for the latter, in a much broader perspective, the most recent efforts have disentangled the different types of climate-related risks and their effect on the overall financial system (NGFS, 2021). Climate change affects asset value through the overarching classes of physical risk and transition risk. Suppose the former is related to the risk of loss of asset value due to extreme climate events. In that case, transition risk revolves around the possible consequences of the sustainability transition on certain kinds of assets (e.g., *stranded assets*). In both cases, the non-linear and uncertain nature of climate change along with the increasing likelihood of occurrence of extreme climate events (e.g., fat-tail probability) represents a concrete challenge for financial actors. How the financial system is trying to cope with this relevant issue will be disentangled later on in the dissertation. This further highlights how deeply intertwined socioeconomic and environmental systems and events generate consequences on the other. In the context of the policy framework, as already mentioned, is one key component increasing the uncertainty for investors. In more specific terms, the uncertain pathways of the sustainability transition imply a lack of precise estimation of future adaptation costs for investors. Indeed, the transition could happen at different paces in different regions or countries. Furthermore, the depth and extent of a future sustainability transition are highly dependent on actions taken in the present. As one pivotal policy intervention, carbon price represents one key piece of information for investors to orient their choices. Indeed, Leitao et al. (2021) have proved how green bonds can influence carbon prices (e.g., EU ETS). In addition, with the EU Directive Market in Financial Instruments Directive II (MiFID II), emission allowances have become financial instruments under Annex I, Section C (11). Its transaction reporting mechanism has been reformed after the 2008 financial crisis to be standardized across countries (Art. 26-27 Market Infrastructure Regulation). In fact, as also confirmed by Borghesi and Flori (2018); Palao and Pardo (2017) from Phase III of the scheme, the EU ETS has progressively resembled a financial market.

This brief overview highlighted how carbon and financial markets progressively influence each other. Correct and sustainability-oriented functioning of those two markets is pivotal to the sustainability transition. Indeed, the overarching objective of this dissertation will try to shed further light on specific yet critical issues related both to financial and carbon markets. This work is ideally divided into three chapters that tackle a specific issue, building on the reference literature and the latest reforms of the policy framework. The primary subject of analysis will be the European Union (EU) policy framework, focusing on the climate, environmental and financial areas, and their interactions. The EU has always played as a global leader towards the pathway of a lower-carbon economy. While the carbon tax is only levied in some of the Member States, from 2005, the Union has adopted an EU-wide mechanism to price emissions. The so-called European Emission Trading Scheme (EU ETS) provides a role model of a functioning carbon market worldwide Borghesi et al. (2016). It represents one of the oldest carbon markets globally, and it covers almost 40% of the EU GHGs emissions. Ideally, the first chapter of the thesis will deal with the specific issue of the scheme's effectiveness in tackling Greenhouse Gasses (GHG) emissions. A suitable methodological approach makes it possible to analyse influences of carbon price behaviour (e.g., European Union Allowance) on CO_2 emissions along with a broad multi-dimensional set of variables. The ultimate aim would be to assess to what extent carbon price behaviour represents a concrete signal to different aspects related to the socioeconomic-environment relationship (e.g., economy, finance, commodity, climate). Concerning other contributions in the literature, this work will try to analyse interactions comprising a broad set of variables. This will provide a new approach to environmental policy analysis, including as many variables as possible. The more technical aspects of the methodology will be disentangled in the chapter. What is worth mentioning at this stage is that this specific approach combines time series econometrics with lasso-based methodologies. The inclusion of lasso-based regularization to a Vector Autoregressive (VAR) framework allows this approach to deal with a sparse set of variables (e.g., multiple variables of different nature). In terms of fresh perspectives on policy evaluation, the second chapter provides a new angle of analysis starting from a well-established framework. In this chapter, the IPAT (Impact, Population, Affluence, Technology) relationship will be taken as an analytical framework to run a cluster analysis on the EU Member States considering their environmental pressure, energy efficiency, and sustainable performance sources. This approach made it possible to find homogenous groups among the Member States regarding environmental performances and energy efficiency. In the framework of convergence of policy objectives, this chapter will assess to what extent Member States are performing in line with overall EU objectives. Thus, the clustering algorithm will be run on data of three different reference periods in time to highlight possible changes in the number of groups and composition (e.g., comparative static). Indeed, results highlighted cases of the Member States that have improved their performances over time. Moreover, despite the limitations of the methodology, cluster analysis may provide new insights on (environmental) policy analysis applying a data-driven approach. Maybe the key point of this kind of approach is the absence of pre-existing hypothesis on the relationship among variables when running the algorithm. This entails both strengths and weaknesses of this class of statistical analysis.

The final chapter of the thesis will provide a fresh insight into one of the most recent fields of research and policy areas related to the sustainability transition. Traditionally, the discourse around sustainable finance dates back to the famous speech by former governor of the Bank of England Mark Carney in 2015. After the so-called "*tragedy of the horizons,*" there has been growing attention in the financial field to the effects of climate change on assets and, in turn, credit assessment. Climate changes in a nonlinear and chaotic manner: due to this nature, it is difficult for scientists to measure (and predict) future changes in climatic conditions (Franzke, 2014). While climate science is developing new methods to cope with this nonlinearity, this poses a severe threat because the effects of climate change on humans are *de facto,* totally unexpected. Climate change effects can be disentangled considering their occurrence. A changing climate might result in (abrupt) temperature changes that will progressively affect human and human livelihoods. On the other hand, there are more immediate and intense effects related to the increase in the occurrence of some extreme events (e.g., *fat-tail probability*). More frequent and intense floods, typhoons, droughts generate higher adaptation costs. In finance, climate-related risk entails the future loss of value for financial assets and, in turn, for investors. In fact, besides losing value due to physical damages (e.g., *physical risk*), assets could also lose value due to societal changes. The mounting attention to more sustainable production and consumption patterns might result in a loss of value for certain kinds of assets (e.g., fossil fuels). On the other hand, those sustainability-oriented assets (e.g., renewables) entail their specific risk classes to investors. This overall picture needs to be contextualized considering the timing of the sustainability transition (e.g., *transition risk*) and the lack of a cohesive framework on sustainable finance. In this framework, the chapter provides new insights into the possible role of financial innovations in shifting or lowering those risks related to climate change. In its much broader definition, financial innovations comprise all those innovative products, processes, and business models to lower or shift specific classes of financial risks. Some recent events (e.g., the 2008 financial crisis) have highlighted how financial innovations, lack of transparency, and asymmetric information can lead to significant economic turmoil. Indeed, this final chapter would aim to find a possible role of those innovations considering examples already used by financial operators. However, the main findings of the work are that the lack of a comprehensive framework on sustainable finance and the substantial advantage of investing in sustainability-oriented assets represents a significant hurdle to further research.

In fact, from the brief overview of the three chapters, it is possible to extract common themes across the overall discussion. One is to pay attention to interactions among different policy areas. The EU has recently issued the 2030 climate and energy framework in emission trading and energy policy. This framework at the EU level is connected with the overall pledges in the international landscape (e.g., Conference of Parties, UN Framework Convention on Climate Change). On the other hand, the overall framework on finance at the policy level is still in its infancy, considering the international landscape. Most of the initiatives have been deployed by the private sector (e.g., NGOs). In sustainable finance, what is missing is the lack of a comprehensive and established framework, especially for the definition of green (and non-green) activities. The most recent research efforts have developed analytical methodologies to assess assets' exposure to climate-related risk. Those have already been adopted mainly in central banks and financial authorities (Chapter 3). On the other hand, the EU has been developing a comprehensive Taxonomy of sustainable investments based on two pillars. So far, activities included in the taxonomy must significantly contribute to either adaptation or mitigation to climate change. On the other hand, they must not harm other objectives at the policy level (e.g., circular economy, biodiversity conservation, marine ecosystems). In addition, a recent EU Directive is enhancing the obligation to disclose non-financial information (e.g., Non-financial Reporting Directive). In this framework, policy areas must communicate with each other. Ideally, this may avoid possible conflicting objectives among different areas of intervention. On the other hand, better communication among different areas could create a common ground of understanding, paving the way to convergence objectives at the policy level. The other common theme is the multi-disciplinarity embedded in environmental economics and environmental policy analysis. Those three chapters will analyse different aspects of the human-environment relationship. Carbon price represents a relevant signal to producers, consumers, and investors. In the case of carbon markets, the price choice is driven by transactions and the number of permits. Ideally, a reliable carbon price should be able to orient production, consumption, and in turn, investment decisions. In addition, a reliable carbon price and environmental policy could also help shape a consistent policy framework for sustainable finance. Moreover, this work's topics and analytical choices aim to provide new viewpoints on those issues, considering their complexity. Indeed, this work applies some methodological techniques (e.g., lasso-based optimization, cluster analysis) that are suitable to deal with multiple variables of different nature (e.g., economic, social, environmental, finance, climate). Ideally, with this kind of approach, it will be possible to deliver a comprehensive yet synthetic analysis comprising all the dimensions of the human-environment relationship. However, the limits of these approaches are well-known in the literature and will be highlighted in every chapter. As for the third chapter, the limit of this research effort is more related to structural issues still open in the context of sustainable finance.

Chapter 1 – "Emission Trading in a high dimensional context: to what extent carbon markets are integrated with the broader system?"

Abstract

The following work will provide further insights into the influence of European Emission Allowance (EUA) prices on carbon dioxide trends and relevant variables of the economic-financial climate-environmental system considering a large set of time series. The methodological approach will employ Hierarchical Vector Autoregression by W. B. Nicholson et al. (2020) deal with a high-dimensional context. Results of the two specifications highlighted how CO2 appears to be more influenced by commodity prices, climate variables, along with past industrial performances. Furthermore, a shock of carbon prices could potentially exert significant turbulence on the carbon dioxide series, fading in intensity as time goes by. Overall, despite some instances (e.g., CO2), there appears to be a straightforward (negative) effect on the influence of carbon prices on the system. However, further analyses identified how the external contribution to the variance appears to be quite limited for the variable of interest (i.e., carbon price) and the others. As the cornerstone of the EU climate policy, this work sheds light on the influence the EU ETS exerts on a set of multidimensional variables, considering the possible sources of shocks and implementing adjustment mechanisms for EUA prices.

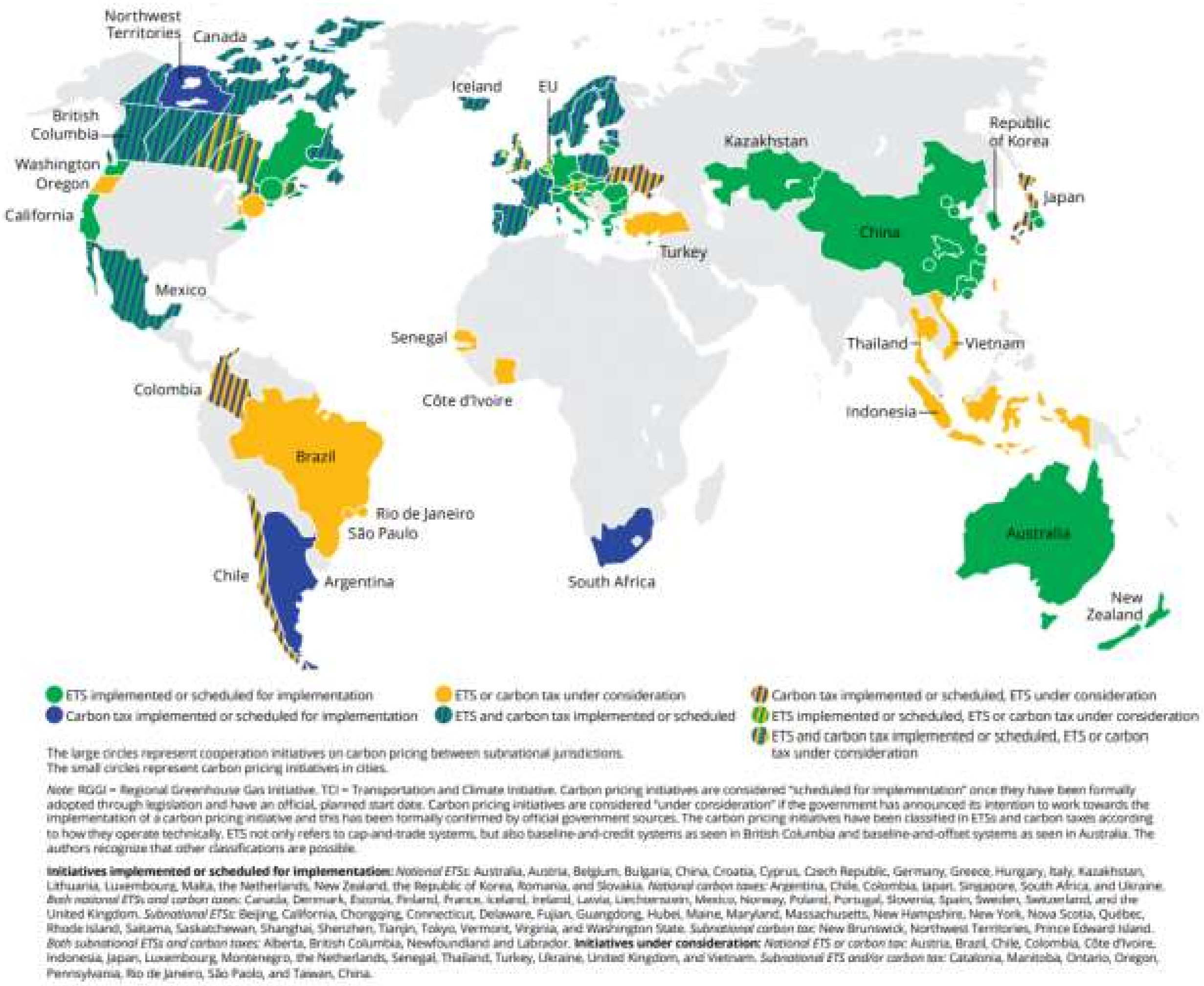
Keywords: EU ETS; emission trading; Hierarchical VAR; Impulse-Response

Introduction

The introduction described how carbon and carbon dioxide are fundamental for humans and the Planet. However, the last decade has witnessed a surprising amount of human-made carbon dioxide emissions in the atmosphere with irreversible consequences for future climate patterns. This occurrence has altered the equilibrium of temperature and, in turn, climate pathways. Thus, if not promptly addressed, adaptation costs to climate change will become unsustainable for humanity. The international community calls for a joint pledge of nations to tackle climate change lowering CO_2 emitted due to human activities. After the Kyoto Protocol was adopted and entered into force in 2005, most industrialized nations pledged to reduce their GHG primarily via three market-based mechanisms. Emission Trading (ET), Clean Development Mechanism (CDM), and Joint Implementation are the tools agreed upon by the Conference of Parties (COP-3) to try to curb emissions within the objectives of the Protocol. Since then, the carbon market has become one concrete policy option for States to comply with Kyoto Protocol obligations. Carbon is now *de-facto* a commodity, and the number of carbon markets worldwide has grown in the last couple of years.

Figure 2 shows the current state of implementation of emission trading in the world.

Figure 2 Current state of carbon price initiatives (emission trading, carbon tax)

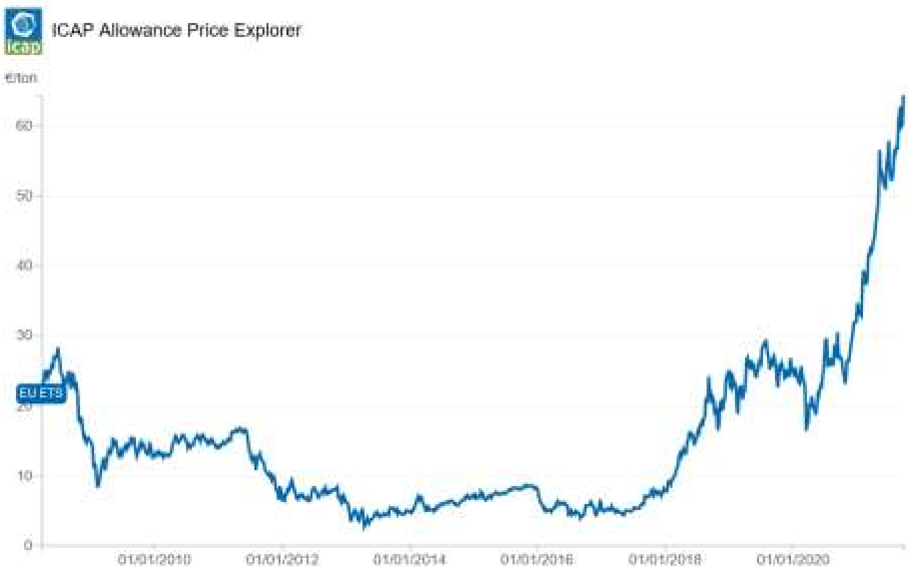


Source (World Bank, 2020)

As it is possible to appreciate from the Figure, governments are either considering implementing a sole emission trading or in combination with a carbon tax for specific sectors (e.g., residential). China has recently launched the largest carbon market globally, covering around 4000 $MtCO_2$ (30% of its national emissions). Germany, Luxembourg, and the Netherlands are implementing national carbon markets (besides the EU-wide market) and carbon taxes. World Bank (2020) argue that most of the trading schemes at the international level only cover heavily polluting sectors. According to the latest account by World Bank (2021), the 64 emission trading schemes worldwide cover more than 20% of the global GHG emissions generation. Charging a price on CO_2 emissions might give a consistent shift to the ongoing course of action. Pricing carbon will provide a reward for implementing low-carbon production processes (High-level Commission on Carbon Prices, 2017). Especially for developing economies, a carbon price might prevent development from being locked into a carbon-intensive path (Hourcade and Shukla, 2013). However, a sensible difference exists between the optimal theoretical framework and the practical implementation of a carbon price scheme High-level Commission on Carbon Prices (2017).

Even though single initiatives of the Member States, the European Union, in 2005 launched the so-called European Emission Trading Scheme (EU ETS) Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC (Text with EEA Relevance). So far, the mechanism has been functioning for more than a decade, providing a price primarily to CO_2 emissions for specific categories of enterprises (see Annex I, Directive 2003/87/EC) within the European territory. The European attempt represents a role model of a functioning scheme for trading emissions (Borghesi et al. 2016; C.-J. Ji et al., 2019). As such, the EU ETS has attracted the interest of policymakers and in the academic world (Convery 2008; C.-J. Ji et al., 2019). Several streams of research, Chevallier (2011a); Convery (2008); C.-J. Ji et al. (, 2019), among others, have tried to disentangle drawbacks, strengths, determinants of the European Union Allowance (EUA) price. Price stability has been a growing concern for European policymakers (Ellerman and Buchner, 2008). Since its first steps, EUA prices have not reached a stable trend over the years, reaching zero transactions at the end of Phase I. Indeed, Figure 3 shows the trend of EU ETS prices over the last decade. From 2009 prices have not reached 20 €/CO_2 tonne. Supposedly, the announcement of the introduction of quantity-adjustment mechanisms (e.g., Market Stability Reserve) in 2017 is among the factors that led the rise up to 2019. After introducing the Market Stability Reserve in 2019, prices have increased up to 80 €/CO_2 tonne of December 2021.

Figure 3 European Union Allowances Price trend 2008-2020



Source https://icapcarbonaction.com/en/ets-prices

In its long-term strategy, developed after signing the Paris Agreement, the EU committed to carbon-neutrality by 2050. With the EU Green Deal, the Union has deployed various funds to catalyze a potential more excellent private initiative towards sustainability. In this sense, as Pearce (2003) stated, an appropriate account of the social costs of carbon is still an open issue and a perceived hurdle to achieving a societal transition towards sustainability. Estimates of a carbon price in the 34 IPCC scenarios (430-480 ppm of CO2 by 2100), as computed by IPCC (2014); Tvinnereim and Mehling (2018), range from US$37 to US$67 per tonne of CO_2 in 2020, whereas in 2050 would be US$127-US$305. However, if carbon pricing could generate revenue flows reducing the overall tax burden, more flexible pricing mechanisms could likely imply less adverse effects on competitiveness (OECD, 2016b).

Very few contributions (see Ellerman and Buchner (2008); Laing et al. (2014); Delarue et al. (2010), among others) have endeavoured to assess the effect of the EU ETS' carbon price behaviour on GHGs emission generation. Grosjean et al. (2016) proved exogenous shocks undermining price stability might come from different sources (e.g., economic recession, overlapping policies, a large influx of Certified Emission Reduction/Emission Reduction Units). Furthermore, while adjustment mechanisms (e.g., MSR) have been implemented, Azarova and Mier (2021) argued that further investigations of their effects favouring GHGs abatement would deliver a more extensive understanding of the functioning of those mechanisms. In its rough structure, the MSR ensures a specific range of EUA price variation via automatically injecting or retrieving permits whenever the quantity in the market reaches certain (lower or upper) thresholds. Indeed, as the process is triggered automatically once the quantity in the market reaches the bounds, the system will be subject to a shock that affects prices and other connected variables. On the other hand, other mechanisms (i.e., price roof/floor) act directly on prices (Andor et al., 2016). As curbing emissions is the foremost objective of the entire mechanism, the present work will test the effects of shocks on EUA prices that might affect carbon emission and a set of relevant variables. Ideally, a positive shock on EUA price will negatively impact emission generation. This work will test this hypothesis adopting a vector autoregressive (VAR) framework considering a large set of time series from economic (i.e., industrial production), to energy (natural gas, crude oil, electricity), to financial, to climate/weather (temperatures, rainfall patterns, wind speed). In a much broader perspective, the paper will analyse the current state of the interplay among carbon price mechanisms and other relevant dimensions (e.g., industry, energy, finance) via assessing their response to a shock on EUA prices considering the broader system (e.g., including climate, environmental dimension) Schusser and Jaraitė (2018). In this framework, the Hierarchical Vector Autoregressive (HVAR) model by W. B. Nicholson et al. (2020) will provide a sound methodological approach to this high-dimensional context. Building on the assumption the matrix of the lagged coefficient is sparse, HVAR employs a lasso-based structure with various degrees of flexibility in the hypothetical structure this matrix should have. Besides forecasting, the methodology has been used in Bagheri and Ebrahimi (2020), assessing the connectedness between financial markets and commodity markets. Indeed, via employing this methodology, this will be modeling the system's response to a shock of CO_2 prices in a more flexible context capable of better accounting for the behaviours of each dimension (e.g., economic, environmental, climatic) (Chevallier 2011b). W. B. Nicholson et al. (2020) proved HVAR delivers better forecast performances with respect to other models fitted for high-dimensional time series (when k increases). Concerning other approaches, HVAR is better suited to deal with multi-dimensional variables because it takes into account the behavior of the single time series. Thus, in light of the research question of this work, HVAR represents a more appropriate methodology to assess how the behavior of carbon price at the EU level might affect the economic, financial, environmental, and climatic dimensions. Indeed, considering the relatively scant application of HVAR methodology in (macro)economic analysis, this work represents an ulterior instance in the context of environmental policy analysis. The work proceeds with a brief overview of the theoretical and institutional underpinnings of the EU ETS, highlighting the main criticalities. Further, a detailed description of the data employed and the methodology followed by estimating the Impulse-Response Function (IRF) and Forecast Error Variance Decomposition (FEVD). The last two sections will provide comments and discussions on the results with conclusions and implications for policymakers.

EU ETS- Literature Review

From a legislative point of view, the EU ETS was instituted with Directive 2003/87/EC of the European Parliament and of the Council of 13 October, 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC (Text with EEA Relevance). Currently, it operates in 31 Countries, 27 EU Countries, plus Iceland, Norway, Liechtenstein, and the United Kingdom. It is designed to cover 45% of the total EU-wide GHG emissions. Right now, it accounts for 11,000 heavy energy-using installations all over Europe. Over the three phases, the system has highlighted some criticalities that appear to be expected in emission trading design. Indeed, Chevallier (2011a); Asian Development Bank (2015); Borghesi et al. (2016); Perino and Willner (2016); Brouwers et al. (2016) highlighted all those relevant issues that could be reduced to institutional factors (e.g., lack of long-term political commitment, adjustment mechanisms) and agents' expectations (e.g., Australian Carbon Mechanism). In its early stages of implementation, the system has also experienced frauds (e.g., carousel fraud, Black Stone). One other point is related to price behaviour that has not reached a stable trend scheme[3] with a tendency to allocate more permits to favour their domestic industrial enterprises during the first phases (Asian Development Bank, 2015); Borghesi et al., 2016). As for policy commitment, Lecuyer and Quirion (2013); Schusser and Jaraitė (2018); Shahnazari et al. (2017) have proved empirically that other instruments might be complementary to carbon price at the local level, especially in the power sector. Expectations are mostly related to risks and uncertainty at the policy level (energy efficiency, technology) and the market level (commodity prices) (Blyth and Bunn, 2011). One of the latest, the Market Stability Reserve, conceived a mechanism that creates a corridor for the number of allowances that can be traded in the market.

Aside from the overall faring of the system, researchers have been striving to find determinants of European Union Allowances (EUA). Alberola et al. (2008); Creti et al. (2012); Aatola et al. (2013); Koch et al. (2014) found that EUA prices are influenced by weather (temperature, extreme weather events) indicators, other commodity prices (i.e., oil, gas), industrial productivity, financial markets[4] (e.g., commodities). Q. Ji et al. (2019); Oberndorfer (2009); Soliman and Nasir (2019); Zhu et al. (2018) have identified the influence of commodity markets (i.e., coal, gas, oil, electricity) and other carbon markets. Hitzemann et al. (2015); Eugenia Sanin et al. (2015) investigated the effects of specific announcements on EUA price volatility. Despite the need to consider the nature of CO_2 behaviour, as stated by Chevallier (2011b), most studies have focused on the functioning principles of the scheme.

Research efforts have also tried to disentangle the effects of emission trading on diverse aspects. Adopting a diff-in-diffs approach, Marin et al. (2018) and Löschel et al. (2019) analyzed the impact of EU ETS on the economic performance of Italian and German enterprises, respectively. Teixidó et al. (2019) reviewed the empirical literature on the effectiveness of emission trading in fostering a low-carbon technological transition. Naegele and Zaklan (2019); Koch and Basse Mama (2019) dealt with carbon and investment leakage potentially caused by the scheme.

Effectiveness of the policy

Despite the effective decreasing trend in CO_2 over the last decade, Brink and Vollebergh (2020) notice it is pretty hard to trace the direct effect of the EU ETS considering the multiple factors involved. The amount of emission reduction might also be influenced by unilateral policy interventions (Perino et al. 2019). However, McGuinness and Ellerman (2008); Ellerman and Buchner (2008); Ellerman and Feilhauer (2008); Anderson and Di Maria (2011); Martin et al. (2016); Dechezleprêtre et al. (2018) highlighted how EU ETS has been effective in decreasing emissions in different Phases of the scheme using country-level data. All the studies highlighted a contribution of EU ETS in abating emissions, despite the difficulty of measuring the counterfactual. However, possible exogenous shocks can undermine the stability pathway of prices with consequences for reaching the targets (Grosjean et al. 2016). Aside from shocks deriving out of economic turmoil, Perino et al. (2019); Lecuyer and Quirion (2013); Shahnazari et al. (2017) point out other sources can be tracked down to possible conflicting policy aims between the EU ETS and national policies (e.g., waterbed effect). Uncertainty on the policy mix is likely to increase according to different transition scenarios to a low-carbon economy (NGFS, 2019).

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[3] for a deeper insight on EUAs price behaviour see https://www.sendeco2.com/it/prezzi-co2 or https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances

[4] EUAs are considered particular category of financial instruments under MiFID II Regulation (Directive 2014/65/UE du Parlement européen et du Conseil du 15 mai 2014 concernant les marchés d'instruments financiers et modifiant la directive 2002/92/CE et la directive 2011/61/UE Texte présentant de l'intérêt pour l'EEE, 2014) pursuant to point (11) of Section C of Annex I of that directive. Derivatives of emission allowances are listed under point (4) of Section C of the said Annex.

Data and methodology

Data

A diverse array of time series will be employed to perform this analysis encompassing the multiple dimensions involved. For a decade (2008-2019), monthly data will be considered for the analysis. Data on monthly EUA stock prices are taken from ICAP[5], SendeCO2[6] and Jiménez-Rodríguez, (2019). Aggregated monthly CO_2 trends have been estimated from data on energy consumption (e.g., Gross Inland Deliveries) for the 31 Countries and eight fuels (four primary and four secondary) from the Eurostat database following the methodology in Eggleston et al. (2006)[7] (so-called Reference Approach). The industrial dimension, the Global Index of Real Economic Activities[8] (e.g., Kilian Index) as conceived in Kilian (2009) and adjusted following Kilian (2019); Kilian and Zhou (2018), will be employed as a better measure of economic activity with respect to conventional indexes (e.g., real GDP, industrial production). To include the financial market side, the EURO STOXX50 index provides a composite measure of value for the biggest Eurozone enterprises in the stock market. The index is designed by STOXX and retrieved from Yahoo Finance[9]. For commodity prices, natural gas and oil come from the World Bank Commodity Price Data repository for the Netherlands Title Transfer Facility[10] and Brent, respectively. Electricity prices are those of the Nord Pool Power Market encompassing Northern and Baltic regions. Climate and weather data are stored in the IEA Weather Energy Tracker, held by IEA and Mediterranean Centre for Climate Change (CMCC). As the database contains country-level data, the series employed has been achieved by averaging the values of the 31 Countries under the ETS. Climate/Weather data comprise monthly averages of temperatures (i.e., min, max, heat index), rainfall (maximum rainfall), wind speed (10 mt, 100 mt). Table 1 summarizes the main statistics for the series.

Table 1 Summary Statistics of the series

Statistic	Min	Pctl(25)	Median	Pctl(75)	Max	Median	St. Dev.
kilian_indx	-161.643	-59.844	-30.296	16.326	189.220	-30.296	70.394
brent	30.700	56.745	76.415	108.073	132.720	76.415	26.796
co2	242.407	276.083	297.298	320.205	358.932	297.298	28.483
eua	3.538	5.951	8.195	14.730	26.881	8.195	6.129
heat_indx	-1.041	5.005	10.505	16.824	21.048	10.505	6.408
max_temp	7.353	13.715	20.834	26.801	31.103	20.834	7.049

[5] https://icapcarbonaction.com/en/

[6] https://www.sendeco2.com/it/prezzi-co2

[7] The dataset is available upon request, for deeper insights on the methodology see (Quatrosi, 2020)

[8] The index is available in the Kilian's personal webpage and updated monthly by the Federal Reserve Bank of Dallas, see https://www.dallasfed.org/research/igrea

[9] For this work it has been decided to use closing prices.

[10] from April 2015, Netherlands Title Transfer Facility (TTF); April 2010 to March 2015, average import border price and a spot price component, including UK; during June 2000 - March 2010 prices excludes UK.

tot_rainfall	0.052	0.086	0.103	0.113	0.142	0.103	0.018
min_temp	-14.069	-3.749	1.069	7.751	12.039	1.069	6.823
wind_sp10	2.907	3.292	3.603	3.906	4.535	3.603	0.390
wind_sp100	4.324	4.958	5.538	6.123	7.070	5.538	0.685
natural.gas_price	3.910	6.694	8.800	11.232	15.930	8.800	2.822
np_elec	9.550	28.620	34.125	44.180	81.650	34.125	12.131
stoxx50e	1,976.230	2,678.523	3,033.205	3,367.273	3,825.020	3,033.205	439.376
e3ci	-0.315	-0.045	0.060	0.166	0.417	0.060	0.156

As tests on stationarity will be commented on later on (Table 3), the preliminary analysis proceeds with the correlation matrix of the series.

Table 2 Correlation matrix time series

	kilian_indx	brent	co2	eua	heat_indx	max_temp	tot_rainfall	min_temp	wind_sp10	wind_sp100	natural.gas_price	np_elec	stoxx50e
kilian_indx	1	0.358	0.230	0.653	0.035	0.024	0.055	0.030	-0.011	-0.020	0.347	0.374	0.101
brent	0.358	1	0.273	0.142	0.108	0.122	0.037	0.089	-0.072	-0.085	0.712	0.271	-0.232
co2	0.230	0.273	1	0.115	-0.750	-0.746	-0.079	-0.733	0.655	0.676	0.553	0.409	-0.132
eua	0.653	0.142	0.115	1	0.003	0.009	-0.064	-0.009	0.025	0.021	0.235	0.552	0.163
heat_indx	0.035	0.108	-0.750	0.003	1	0.987	-0.020	0.987	-0.859	-0.880	-0.104	-0.268	0.029
max_temp	0.024	0.122	-0.746	0.009	0.987	1	-0.083	0.963	-0.867	-0.888	-0.105	-0.253	0.023
tot_rainfall	0.055	0.037	-0.079	-0.064	-0.020	-0.083	1	0.005	0.175	0.144	0.035	-0.143	-0.075
min_temp	0.030	0.089	-0.733	-0.009	0.987	0.963	0.005	1	-0.830	-0.852	-0.102	-0.285	0.029
wind_sp10	-0.011	-0.072	0.655	0.025	-0.859	-0.867	0.175	-0.830	1	0.996	0.112	0.182	0.046
wind_sp100	-0.020	-0.085	0.676	0.021	-0.880	-0.888	0.144	-0.852	0.996	1	0.103	0.197	0.043
natural.gas_price	0.347	0.712	0.553	0.235	-0.104	-0.105	0.035	-0.102	0.112	0.103	1	0.344	-0.399
np_elec	0.374	0.271	0.409	0.552	-0.268	-0.253	-0.143	-0.285	0.182	0.197	0.344	1	-0.153
stoxx50e	0.101	-0.232	-0.132	0.163	0.029	0.023	-0.075	0.029	0.046	0.043	-0.399	-0.153	1

As it is possible to appreciate (Table 2), there are quite a few high correlations between temperature and wind speed. CO2 shows a significant but negative correlation with the temperature set and positive with industrial production and commodities (e.g., natural gas price, oil, electricity) for the variables of interest. There is a relatively weak but positive correlation with EUA prices and a negative with the STOXX index. On the other hand, EUA prices positively correlate with the Kilian Index and Nord Pool electricity prices. Positive yet weak correlation for the financial dimension and the other commodities. Indeed, considering the high correlation of some climatic variables (e.g., temperatures, heat index, wind speed), the model will be considering temperature and heat index alternatively.

Methodology

To account for the multiple dimensions of the series subject of analysis, Hierarchical Vector Autoregressive Model (HVAR) will be employed addressing this high dimensional context. This methodology was first introduced in W. B. Nicholson et al. (2020) as a more suitable solution for forecasting exercises in high dimensional contexts with respect to other approaches to reduce the dimensionality of time series (e.g., correlation analysis, factor models, Bayesian models, scalar component models, independent component analysis, dynamic orthogonal component analysis). HVAR encodes lag order selection into a convex regularization that simultaneously addresses dimensionality and lag order selection. Unlike Bayesian models and lasso-based models, it provides interpretable insights on the contribution of each time series on the forecasting exercise. While aiming at interpretability, HVAR introduces maximization in lag order selection dealing with increasing maximal order. In fact, in other models, as lag order increases forecasting performances tend to degrade. Lasso-based VAR are conceived under the assumption the matrix of the coefficient in high dimensional context is sparse (Song and Bickel, 2011). Starting from the matrix representation of a $VAR(p)_k$ model for a set of k time series of length T[11]:

$$Y = v1^{\intercal} + \Phi Z + U \qquad [1]$$

Where Φ controls the dynamic dependent of the ith component of y_t on the jth component of y_{t-1}. Some contributions have highlighted how the estimation of the least square coefficient matrix might be challenging unless T is large. Furthermore, for large (even medium) k, the matrix of the coefficients is sparse even with regards to the true Data Generating Process (DGP) (Davis et al. 2012). Some authors, as Song and Bickel (2011), have decided to implement convex penalty mechanisms (e.g., Lasso and Group Lasso). In this framework, HLag builds on hierarchical group lasso modelling, providing a structure to the sparse matrix with different degrees of flexibility (i.e., Componentwise, Own-Other, Elementwise). Each row of the equation of the VAR might truncate at a given lag order (e.g., Componentwise) or allow the lag order of the single series to truncate at a different order with respect to the other series (i.e., Own-other). The lag structure might also allow each component of the series to have its own lag order (e.g., Elementwise). While other approaches (i.e., information criteria) provide a universal lag order, Hlag allows lag to vary across marginal models. For the sake of this work, the Elementwise HLag structure has been chosen as the more flexible and better performing in multiple scenarios also concerning other lasso-based methods as seen in W. B. Nicholson et al. (2020). Following the notation on Equation 1, being L a kxk matrix of elementwise coefficient lags

$$L_{ij} = max\{\ell: {\phi_{ij}}^{(\ell)} \neq 0\} \qquad [2]$$

as the smallest maximal lag structure such that ${\Phi_{ij}}^{(\ell)} = 0, \ell = 0, \ldots, p$ for the model considered. For other structures, Elementwise HLag allows all the elements within L to have no stipulated relationships. HVAR performances have been tested for macroeconomic and financial forecasting W. B. Nicholson et al. (2020). Aside from mere forecasting, Bagheri and Ebrahimi (2020) employ this methodology to investigate the interconnectedness of financial stock indexes. To the best of the author's knowledge, this will be the first

[11] For the notation see Appendix 1

attempt to employ Hierarchical Vector Autoregressive models for variable-to-variable analysis (i.e., Impulse-Response) in environmental macroeconomics.

Results and Discussion

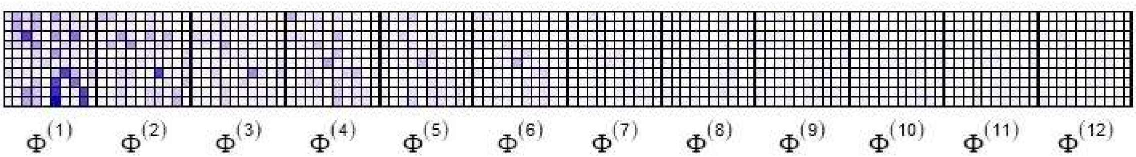
Despite some exceptions (Table 3), all the tests run (e.g., Augmented Dickey-Fuller, KPSS, Box-Ljiung) show the series present non-stationarity either in trends or in drift. Therefore, the series will be analysed in their first differences in the following steps.

Table 3 Multiple Stationarity Tests

	var	box.pvalue	adf.pvalue	kpss.pvalue	box	adf	kpss
1	kilian_indx	0	0.191	0.010	TRUE	FALSE	FALSE
2	brent	0	0.518	0.010	TRUE	FALSE	FALSE
3	co2	0	0.010	0.029	TRUE	TRUE	FALSE
4	eua	0	0.714	0.011	TRUE	FALSE	FALSE
5	heat_indx	0	0.010	0.100	TRUE	TRUE	TRUE
6	max_temp	0	0.010	0.100	TRUE	TRUE	TRUE
7	tot_rainfall	0.078	0.010	0.100	FALSE	TRUE	TRUE
8	min_temp	0	0.010	0.100	TRUE	TRUE	TRUE
9	wind_sp10	0	0.010	0.100	TRUE	TRUE	TRUE
10	wind_sp100	0	0.010	0.100	TRUE	TRUE	TRUE

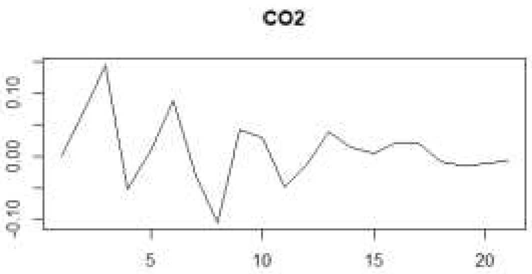
To tackle the different scales and units of measures of the variables, the series will be standardized to refine better the subsequent analyses as suggested by James et al. (2013). Since there is no consistent way for choosing the maximum lag order that applies to HVAR estimation, W. Nicholson et al. (2017) suggest the parameter p will be set according to the frequency of the time series considered (e.g., 12 for monthly series). Once estimated the coefficient, the cross-validation will be performed by dividing the dataset into three parts T/3; 2T/3, respectively. Figure 4 shows the sparsity matrix of the coefficients as the result of the model specification with 12 maximum lags. Furthermore, the matrix shows the model does not consider any ex-ante relationship between data (e.g., Elementwise). From here, it is possible to appreciate how the coefficients of the diagonals tend to weigh more on estimation than off-diagonal. In other terms, the coefficients of the lagged variables tend to influence more the estimation than the single marginal equations.

Figure 4 Sparsity Matrix of Elementwise HVAR



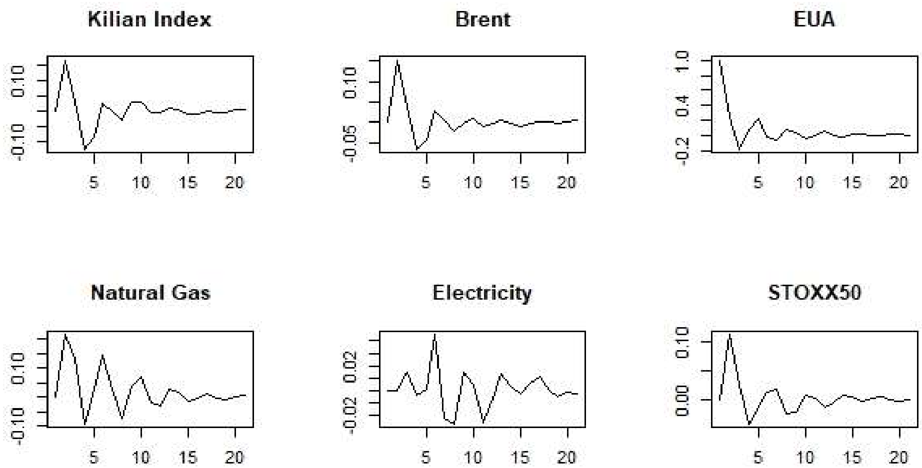
As for the optimization procedure, the chart in Appendix 2 shows a parabolic shape for the penalization term λ.. To show the primary hypothesis, namely, the response of a shock of the carbon price to emission trends from the energy sector, the Impulse-Response Function (IRF) has been modeled out of the last estimation of the HVAR. The computation of the IRF follows Pesaran and Shin (1998) to relax some further limitations, not taking into account the order of the variables. Figures 5-6 show the response of carbon dioxide emission trends and relevant system variables to a shock on EUA prices. Figures 5-6 show the specification of the model considering temperatures (min, max), wind speed at 10 mt, total rainfall. Focusing on the response of carbon dioxide emissions, it is possible to appreciate how the shock generates a wild trend for future emissions, with intensity progressively fading away as time goes by.

Figure 5 Impulse-Response Function CO_2 emissions



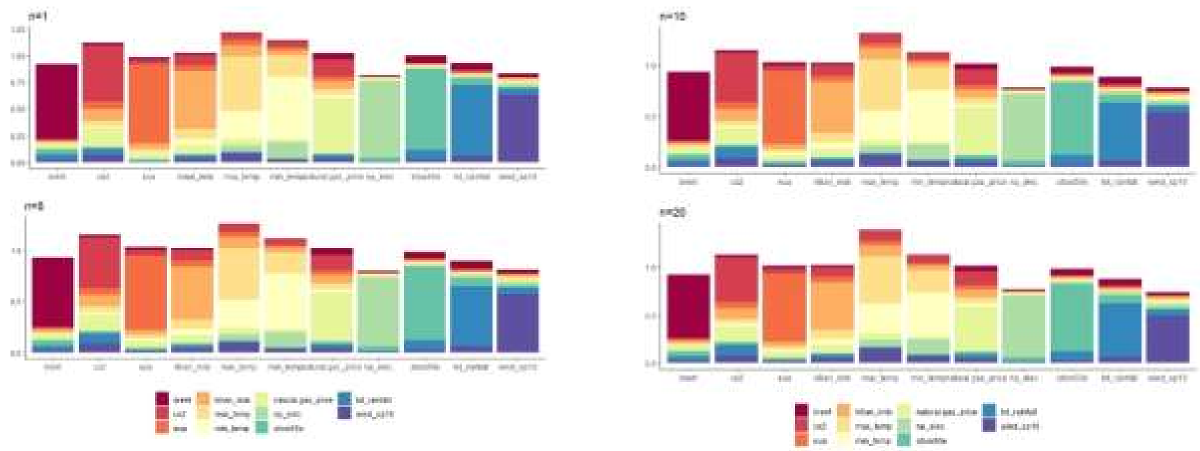
As for other relevant variables of the system considered, Figure 6 models IRF for commodity prices, production, and financial indexes, EUA appears to exert a downward trend for Kilian Index and specific commodity prices (e.g., Brent, Natural Gas) that becomes clearer (yet less intensive) over time. As for the STOXX50 index and Nord Pool electricity, a carbon price shock appears to exert a quite intense response, at least in the nearer future.

Figure 6 Impulse-Response Relevant covariates



To complete the analysis, the Forecast Error Variance Decomposition (FEVD) is depicted in Figure 7, respectively, to 1, 5, 10, and 20 steps ahead. In line with the previous analysis, the computation of FEVD follows the approach as in Pesaran and Shin (1998). The Figure shows how much of the variance in error forecasting of every variable can be explained by the other variables. The higher is the contribution of other variables, the more integrated the system is, and the more robust are results and trends of the IRF Lütkepohl (2005). As shown in Figure 7, the variables themselves exert a higher contribution to the variance. For the variable of interest (e.g., CO_2), other influences mostly come from the climate/weather set of variables and commodity prices. Kilian Index and Natural Gas price explain the carbon dioxide variance between 10%-15% of the carbon dioxide variance. In this sense, according to other findings in the literature, Khalili et al. (2012); Du et al. (2018), among others, the influence of commodity prices could be considered to a greater extent as prices influence commodity demand and supply. Other factors influencing carbon emissions (e.g., industrial production) appear to be in line with Declercq et al. (2011), Dong et al. (2019), Zeng et al. (2021). As for the influence of EUA price, despite relatively low (6%-7%), the value slightly increases over time. All the variables show external influence in their variance composition regarding the broader system. However, the contribution of those variables appears still to be limited. The most significant influence of EUA price ranges between 4%-5% for (max) temperature, natural gas price, Kilian Index. On the other hand, a carbon price is more influenced by commodity prices and temperatures (min, max) than the financial index, rainfall, and wind speed. This latter finding sheds further light on the analysis of the relationship of wind characteristics (e.g., speed, direction) as one other determinant of carbon prices (Chevallier, 2012a). A more country-specific analysis is deemed appropriate to disentangle more consistent results despite the evident yet negligible influence. As for the other variables influencing EU ETS prices, these findings are in line with Mansanet-Bataller et al. (2007), Alberola et al. (2008); Aatola et al. (2013). As for the behaviour over time, Figure 7 does not show any marked difference among the variables.

Figure 7 Forecast Error Variance Decomposition (Specification I)



The specification with the heat index, instead of temperatures, and wind speed 100 (Appendix 3), does not show any difference in the composition except highlighting the relationships identified by the previous specification. Although, of notice, the more marked downward trend of CO_2 has emerged probably due to the choice of a more parsimonious model.

Conclusions

While improvements in the so-called *carbon price gap* signal a better use of market-based instruments reducing CO_2 emissions, there are concerns the current rate of change could meet the ambitious targets of the Paris Agreements (OECD, 2018). On the other hand, the Commission estimated €260 billion (about 1.5% of 2018 the EU GDP) to comply with the EU Green Deal objectives by 2030. In this sense, the EU budget will play a pivotal role in fostering a societal sustainability transition. For this purpose, the EU is planning to earmark 20% of the revenue stream coming from the EU ETS. As from the last account the revenue flow of the EU mechanism amounted to €14 billion in 2019 (€5.7 billion in the half of 2020), with €57 billion of revenues generated within 2012 and June 2020 (Nissen et al., 2020). Furthermore, a sustained price of allowance permits ensured a consistent revenue flow despite the lower level of transactions, especially about the most recent events (Azarova and Mier, 2021; Borghesi and Flori, 2019); Nissen et al., 2020). However, World Bank (2020) estimated that either emission trading or carbon tax does not cover 40% of EU

Greenhouse Gasses emissions. If the short and medium-term effects of COVID-19 pandemics on carbon prices might be predictable, still uncertain are the long-term effects coupled with the outcome of Brexit. By all means, Verde et al. (2021) demonstrate factors such as policy interplay (e.g., waterbed effect) appear to be key issues undermining price stability, hindering concrete abatement efforts, and in turn, a more coordinated framework tackling climate and environmental issues. This work tries to provide ulterior insights on the effect of the emission trading scheme at the EU level, considering the broader system (environmental, climate, economic, financial) adopting a more suitable methodology. Hierarchical VAR has been conceived for high dimensional contexts providing interpretable results taking into account the single characteristics of the series considered. As already pointed out, the EU ETS represents the cornerstone of the EU climate policy. However, since its introduction, in early 2005, carbon prices have not reached a (high) sufficient level. Main factors influencing EUA price level have been identified in an oversupply of permits during the first phases, issues related to the implementation of national policies in ETS-sectors, and a perceived lack of political commitment. Over the years, the progressive set of reforms (Phase I, II, III, IV) has tried to build a more reliable mechanism introducing price adjustments tools and the very auctioning of permits. The literature has also focused on the determinants of carbon prices and studies on the effectiveness of the policy. Those latter have been mainly conducted on a national basis confronting ETS with national policies. This work employs time series econometrics and lasso-based regularization to provide new insights on the effectiveness and integration of the EU ETS considering economy, finance, energy, climate, environment. Despite a rather clear (downward) pattern, there appear to be other factors that exert a stronger influence on carbon dioxide with respect to EUA prices (e.g., climatic/meteorological, industrial performances, natural gas). Furthermore, results align with the preliminary analyses (e.g., correlation matrix) and the literature pointing out an influence of carbon prices on industrial performances, commodities, (extreme) temperatures. The lack of influence on financial markets could explain that not all the sectors are included in the EU ETS. Overall, the magnitude of influence of carbon price towards the other variables is relatively weak for all the periods considered. On the other hand, the IRF plot has shown a negative pattern of the response of those variables to a shock on EUA prices. Results with other model specifications confirmed if not highlighted the findings also in line with the literature. In this sense, the choice of a more flexible methodology (HVAR) and the computation of IRF following the approach in Pesaran and Shin (1998) provided a more flexible environment to account for the diverse dimension of the system subject of analysis as suggested by Chevallier (2011b). These findings provide ulterior insights to policymakers for better taking into account possible sources of carbon price shocks (e.g., overlapping policies) and tailoring existing adjustment mechanisms (e.g., Market Stability Reserve) for the stability of the European Emission Trading Scheme. In this sense, results show the still relative prospective influence of carbon prices towards relevant variables considering the broader system. These findings should also be contextualized in light of the recent reforms of the EU ETS (Phase IV) that are not considered in this work. Factors influencing the effectiveness of the policy can be tracked down to the existence of (conflicting) environmental policies at national levels along with uncertainty over a sound price adjustment mechanism (Market Stability Reserve, price floor) that are still object of discussion for policymakers. A more active dialogue between national and EU policymakers should lead to a comprehensive policy mix avoiding overlapping aims. Despite the well-established influence on commodity markets, the almost non-existent influence of carbon prices on finance *strictu sensu* could be deemed an ulterior hurdle to channel funds towards sustainable investments. Even though EUA has been included as a financial instrument by the recent EU financial directive (MiFID2), apparently, carbon allowances are not enough considered by financial players. In this perspective, the huge process of reform affecting the financial sector (e.g., Taxonomy) should be designed considering the comprehensive array of policies from multiple aspects. Among the consistent literature on EU ETS and emission trading, this work tries to shed light on how this climate policy's current and potential integration with the broader system. This will be at the basis to promote a complete transition to sustainability in light of the problem's complexity and multi-faceted nature.

Appendix 1

$$Y = v1^{\intercal} + \Phi Z + U \quad [1]$$

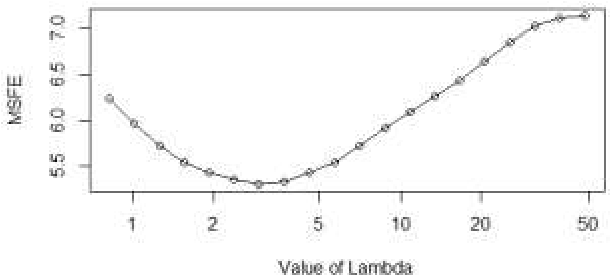
$$Y = [y_1 \dots y_T]\ (k\ x\ T);\quad Z = [z_1 \dots z_T](kp\ x\ 1);$$

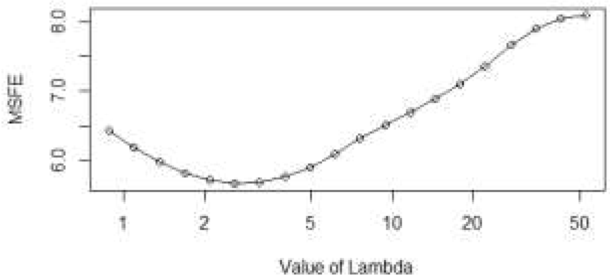
$$z = \left[y^{\intercal}{}_{t-1} \dots y^{\intercal}{}_{t-p}\right](kp\ x\ T);\ U = [u_1 \dots u_T]\ (k\ x\ T);$$

$$1 = [1 \dots 1]^{\intercal}\ (T\ x\ 1);\quad \Phi = \left[\Phi^{(1)} \dots \Phi^{(p)}\right]\ (k\ x\ kp)$$

Appendix 2

Figure 8 Lamba Plot I-II Specification

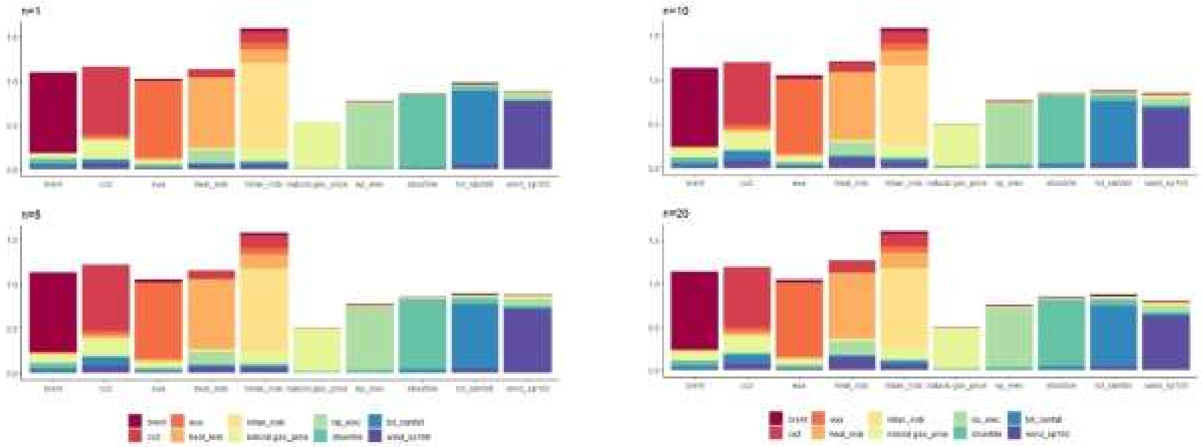




Appendix 3

Figure 9 shows the FEVD plot of the model's second specification, namely with heat index instead of (min, max) temperatures.

Figure 9 Forecast Error Variance Decomposition II



It is possible to infer that the composition of the variance does not show marked changes between the two specifications. Though, of notice, some of the variables have decreased in intensity, probably due to the choice of a more parsimonious model. As for the variable of interest (e.g., CO_2), a slightly lower percentage of variance is due to both industrial production and natural gas price. Higher temperatures mainly influence carbon price towards the Heat Index (5%).

Chapter 2- Clustering environmental performances, energy efficiency and clean energy patterns: a comparative static approach across EU Countries

Abstract

In the context of convergence of objectives among the single Member States within the European Union, environmental policy has always been considered one pivotal and necessary step towards a cohesive EU. Employing clustering techniques, this work identifies affinities in environmental performances (e.g., CO_2 emissions), energy efficiency, and clean energy patterns for European countries. K-medoids clustering will be used for a cross-section of the total carbon dioxide emission in three reference years (2008, 2013, 2018). Data to feed the algorithm have been selected considering the well-established IPAT relationship as an analytical framework. After preliminary analysis, results highlighted the presence of persistent groups of countries over time with marked characteristics in terms of environmental performances, energy efficiency, and clean energy patterns. Considering the limitations of data employed and the potentialities of the methodological approach, this work could shed light on a new perspective of analysis in light of the harmonization path the EU has been undertaking since its foundation. These findings could better address policymakers in terms of convergence of environmental policy implementing new measures to promote low-carbon consumption and production patterns with a specific focus on energy efficiency (e.g., heating and cooling) and sustainable sources (e.g., nuclear power).

Keywords: IPAT; clustering; renewables; energy efficiency; emissions; environmental policy; energy policy; energy mix

Introduction

Chapter 1 highlighted how carbon prices influenced the socioeconomic landscape and specific environmental variables (e.g., CO_2, temperatures). Results highlighted how carbon prices still exert a relatively weak influence towards all the relevant variables object of analysis. However, the EU has implemented a comprehensive policy framework encompassing all the aspects of environmental protection and fighting climate change (European Parliament 2013). The process of sustainability transition has always witnessed Europe as one of the most ambitious players in the global landscape. In this sense, while finding an alignment at the international level, the EU is also seeking out harmonization of environmental policy objectives at the Member States' level. This process will strengthen the EU's position as an international leader, promoting a more conscientious relationship between humans and the environment. The European Union has been committed to reducing GHGs emissions (EU2020 Climate and Energy Package). However, only 13%[12] of the overall energy supply in the Union comes from renewable sources. Besides the idea of a worldwide carbon tax, Europe has put a cap on its level of emissions (e.g., European Emission Trading Scheme), with the power sector being among the most prominent players. The power sector is also transitioning to more efficient use of energy along with more sustainable energy sources. Estimates in DG Energy (2020) show that in Europe, in 2008, renewable generation has outperformed fossil fuel-based energy production. Complying with the progressively more stringent emission reduction objectives, renewables share on energy consumption, energy efficiency is enforced via a comprehensive policy framework at the EU level (EU Emission Trading Scheme, Effort Sharing Regulation, Land Use, and forestry regulation). The encompassing set of policy initiatives that contribute to the creation of the Energy Union stands on five pillars:

1. Decarbonisation
2. Energy Security
3. Energy Efficiency

[12] Source Eurostat, data from 2017

4. Internal Energy Market
5. Research, Innovation, and competitiveness

Member States are motivated to push for renewable self-consuming, recovering waste heat/cold, promoting electrification in transport based on renewables, and promoting new methods for financing (purchasing power agreements). Among the initiatives to reach 2030 targets, Member States will make progressive use of carbon pricing. For instance, Germany, Luxembourg, and the Netherlands adopt their own ET scheme covering those GHGs and sectors not included in the EU ETS European Commission (2020a).

The IPAT relationship represents a simple yet effective framework of analysis bridging human beings and nature. The underlying philosophy of the relationship, as stated by Ehrlich and Holdren (1971) in their seminal work, aims to assess the (negative) impact society is exerting on the environment. Empirically, the IPAT model has considered energy about the technology domain save more recent specifications. With some exceptions, the discourse around the energy transition investigates the influence of its main dimensions (e.g., energy efficiency, renewable sources) concerning the other elements of the IPAT relation (Chontanawat, 2018). According to the diverse epistemological viewpoint collected by Chertow (2000), this influence could be assessed via the contribution either incrementing environmental pollution or reducing. From a strictly applied point of view, IPAT has been employed to assess which dimension exerts the higher contribution on the environmental impact, implying a causal relationship. However, the IPAT is also useful to decompose those effects over time and space, providing a synthetic measure of the main drivers of (human) impact on the environment. In this sense, a wide range of empirical applications have been employed at different territorial levels. However, this dimension could be further explored to highlight common patterns of sustainability transition. In this sense, clustering techniques have been proved to identify hidden patterns of data homogeneity without pre-existing knowledge of the relationship.

While other algorithms somewhat imply an underlying relationship among data (supervised learning), clustering is instead applied to uncover relationships (unsupervised learning). Unlike other statistical techniques, clustering thus solves the issue of dimensionality reduction without significant loss of information (Kaufman and Rousseeuw, 2005). Clustering algorithms can be employed in several fields to find homogeneity in data with many diverse characteristics. In the specific context, this work will apply a clustering algorithm to find common patterns on a set of dimensions related to IPAT with a focus on energy. The data employed come from 31 European Countries (27 EU + Norway, Lichtenstein, Iceland, United Kingdom) spanning from economic (GDP per capita), industrial (% of the manufacturing sector in VA in GDP) demographic (population, density, urbanization), environmental (CO_2 emissions from fossil fuel combustion), energy (primary energy consumption, renewable energies, share of fossil fuels in electricity production). A clustering algorithm will be performed on a cross-section of this dataset for three reference periods (2008, 2013, 2018). Using a comparative static approach, different time frames will monitor clusters' (possible) evolution and their characteristics over time. The context of the EU provides valuable insights as it will be possible to assess whether the EU-wide policy framework has somehow affected the harmonization of the existing differences among the Member States. The environmentalist-industrial ecologists' debate will provide ulterior insights towards a clearer understanding of the IPAT relationship. The simplicity yet effectiveness of IPAT makes it a potential tool for policymakers tackling a complex issue such as the human-environment system.

The paper will review the literature on applications of the IPAT relationship and clustering techniques. More details will then be provided regarding the specific clustering algorithm and the data employed. Cluster analysis identified homogeneous countries with diverse environmental, economic, and demographic characteristics. On the other hand, the comparative static analysis of the three periods identified some groups of countries within clusters that have been stable over time. Northern European countries have scored better environmental performances in emissions and clean energy consumption. The same stands for the Baltic States, even though they reached that cluster only in 2018. Despite the relative homogenization over the decades, a well-established cluster (e.g., Germany, France, Italy, Spain, United Kingdom) has emerged, showing relatively worse environmental performances with a higher impact on the population dimension. Belgium, Luxembourg, and the Netherlands have a relatively high wealth per capita and room for improvement in reducing environmental pressures. For the most, Balkan and Eastern European States score a relatively poor amount of wealth and a promising level of clean energy consumption and energy efficiency. However, the cluster scored the highest share of electricity production from (liquid and solid) fossil fuels. In fact, among those countries, only Croatia managed to move to the cluster with higher environmental performances in 2018. The transition process over the decade for those countries was identified in 2008 when Croatia, Greece, Ireland, and Portugal formed the fifth cluster. The case of Poland could be considered an opposite pattern, as the Country returned among Balkan and Eastern European States in 2018 after a transition phase in 2013. More substantial discrimination among countries could be identified in the demographic dimension, with Germany, France, Italy, and the United Kingdom presenting a relatively higher population level. Overall, the efforts at the policy level to harmonize the Member States from a policy perspective have produced certain results for specific cases. However, cluster analysis is highly dependent on the choice of data employed to feed the algorithms. The IPAT relationship has been chosen to provide a well-established analytical framework for choosing the variables. Further expansions of the analysis will include variables more directly related to the objective set at the EU level on low-carbon transition.

The IPAT relationship

The relationship between economic growth and environmental pressure resulting in global warming and a potential threat to human life and livelihood has been consolidated on the scientific ground, as IPCC (2015) stated. Historically, the scientific community has been striving to propose several frameworks to understand this complex relationship and figure a way out of the impasse society has locked in. Over the decades, McNicoll (2015) notices the IPAT relationship has been further specified considering the impact I as influenced by population P, affluence A, and technology T. More accurate formalizations also led to different interpretations of IPAT from the one proposed by Ehrlich and Holdren (1971) in their seminal paper. The first specification encompasses all the dimensions as (positive or negative) influenced by population size P in light of demography's pivotal role in resource depletion. On the other hand, within the lenses of industrial ecology, IPAT has investigated the role of technology as a possible positive factor in reducing (negative) environmental impacts (Chertow, 2000). While environmentalists think population growth is at the core of environmental pressure, industrial ecologists think income increases improve quality of life (da Silva et al., 2019). In this sense, some applicative instances of the IPAT model include some measure of energy efficiency and energy transition as a potential factor influencing human impact on the environment (IPAT-E). Brizga et al. (2013) used energy intensity and total primary energy supply to investigate carbon dioxide drivers of the former Soviet Union. Yue et al. (2013), in the context of IPAT, extended the model including *emergy* analysis to assess the sustainability of a Chinese industrial province. On the other hand, Chontanawat (2018) employed energy efficiency measures in a decomposition analysis of CO_2 emissions for ASEAN countries. Wen and Li (2019) introduce several dimensions of energy consumption in a structural equation model assessing potential driving forces for carbon dioxide emission at China's regional and national levels.

Clustering

Clustering algorithms have been either used to find structures among data or to synthetize information more neatly. In this sense, clustering algorithms have been widely applied to find common patterns in data Kaufman and Rousseeuw (2005). Clustering algorithms have mainly been applied to combine economic and non-economic objects of different orientations, as in Babenko et al. (2021); Banga and Sinha (2018); Boumans and Leonelli (2020); Dogan and Birant (2021); Jayatilake and Ganegoda (2021). Algorithms can aggregate computing the distance among the diverse characteristics of data. The different algorithm classes partition data according to a specific distance measure (e.g., Euclidean, Manhattan) Steinley (2006). Data can be clustered according to a decision-tree structure (e.g., *hierarchical clustering*) or a local decision criterion (e.g., *density-based clustering*). Instead of partitioning k values within the output of the hierarchical clustering algorithm, both *k*=1 and *k*=n results are present simultaneously. Among density-based algorithms, k-means, one of the widely used attempts to minimize the squared distance of some *k* objects, yielding to centroids. On the other hand, k-medoids selects k objects around which building the clusters in either small (*Partitioning Around Medoids*) or large (*Clustering Large Applications*) datasets. Clustering can be performed matching a (statistical) model-based structure (e.g., *model-based clustering*). Homogeneous data aggregation can also come out of graph representations and computations (e.g., *graph-based clustering*). In this sense, clustering can be employed to enhance similarities among data or to mark dissimilarities. In environmental analysis, Franceschi et al. (2018) employed clustering algorithms to analyze the concentration of PM10 and PM2.5. K-means algorithm was used to cluster different simulations to assess the risk of atmospheric pollution, as in Cervone et al. (2008). On the other hand, Di et al. (2019) used partitioning around medoids (PAM) and expected-maximization (E-M) clustering algorithm in analysing wastewater heavy pollutant contents. Chang and Lee (2019) applied the k-means algorithm to compute the Sustainable Development Progress Index (SDPI) with data of 32 OECD Countries. A combination of k-means and kernel-based (density-based spatial clustering analysis with noise- DBSCAN) has been employed to analyse the supply and demand flow of dockless shared bicycles Chen and Chen (2020).

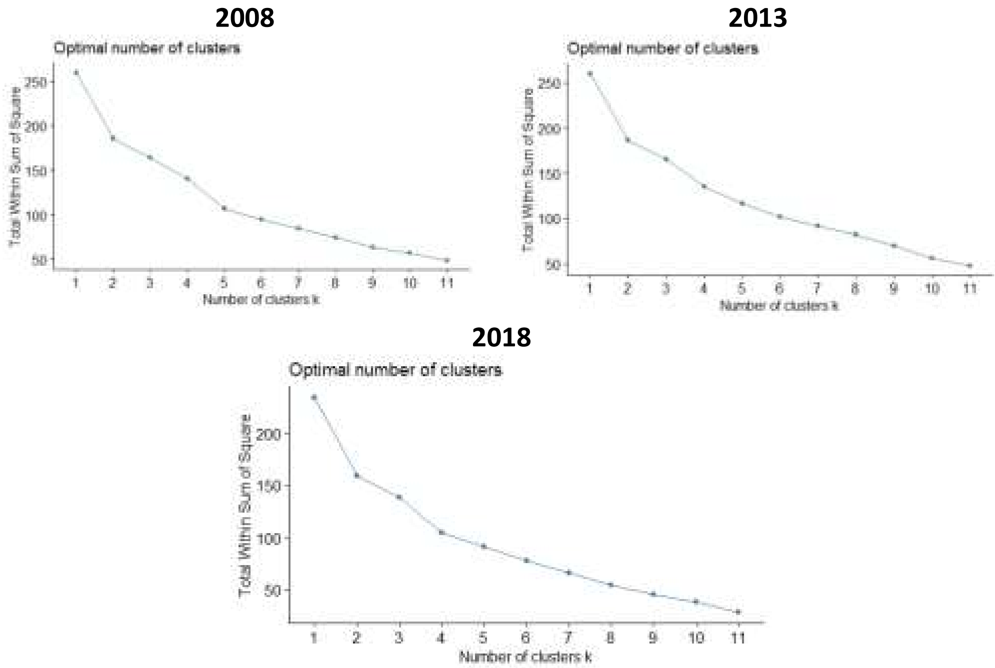
Data and Methodology

The choice of the data to perform the analysis follows the one traditionally employed in the literature for the IPAT identity. For a proxy of environmental pressure, CO_2 emission series have been calculated from the combustion of fossil fuels, following the methodology in Eggleston et al. (2006); Quatrosi (2020). The choice of emissions from fuel combustion will provide a more direct link with the environmental pressure and performances of the energy sector. Gross Domestic Product (GDP) per capita, population density, and urbanization have been chosen as reliable indicators of affluence (A), coming from Eurostat. Data on GDP per capita are collected in chain-linked volume with 2010 as the basis year, whereas population density refers to the ratio of inhabitants per square kilometer. Urbanization measures the (urban) population percentage living in the largest city (e.g., metropolis) taken from World Bank's World Development Indicators database. Furthermore, the algorithm will be fed with data on industrialization, i.e., percentage of manufacturing Gross Value Added (GVA) in total GDP. The dataset covers a decade (2008-2018) for 31 European Countries (27 EU + Norway, United Kingdom). For the energy dimension, the choice of the variables encompasses significant aspects of the energy transition. Primary energy consumption and share of renewable energies have been chosen as measures of the two aspects of energy transition (i.e., energy efficiency, clean technologies). The two variables have been retrieved from the SDG Indicators collected by Eurostat. The energy dimension is completed with data on the shares of electricity production from (liquid and solid) fossil fuels computed from Eurostat. Over a decade, the clustering algorithm will be performed on three reference years (2008, 2013, 2018). Considering the different units of measures, the clustering algorithm will be performed on the variables after standardization. The analysis will be eventually conducted on a comparative static of the three years, highlighting changes in the composition of clusters. As for the clustering algorithm *partitioning around medoids* (PAM) has been chosen for better dealing with outliers, as suggested by Kaufman and Rousseeuw (2005). In this procedure, clusters are constructed by assigning each dataset object to the nearest representative object (e.g., *medoids*). Choosing the optimal number of clusters for all the years will follow a two-layered approach. The optimal number of clusters will be assessed via the elbow method as the first step. The choice of this method, with respect to others, is mainly driven by the capacity of grouping clusters in a more meaningful way, namely reducing the sum of squared errors. However, as there exist a quite wide array of methods (see Milligan and Cooper (1985); Cuevas et al. (2000); Tibshirani et al. (2001) for a review), the choice will also follow a somehow graphical approach considering the more homogeneous configuration of clusters (Kaufman and Rousseeuw 2005).

Results

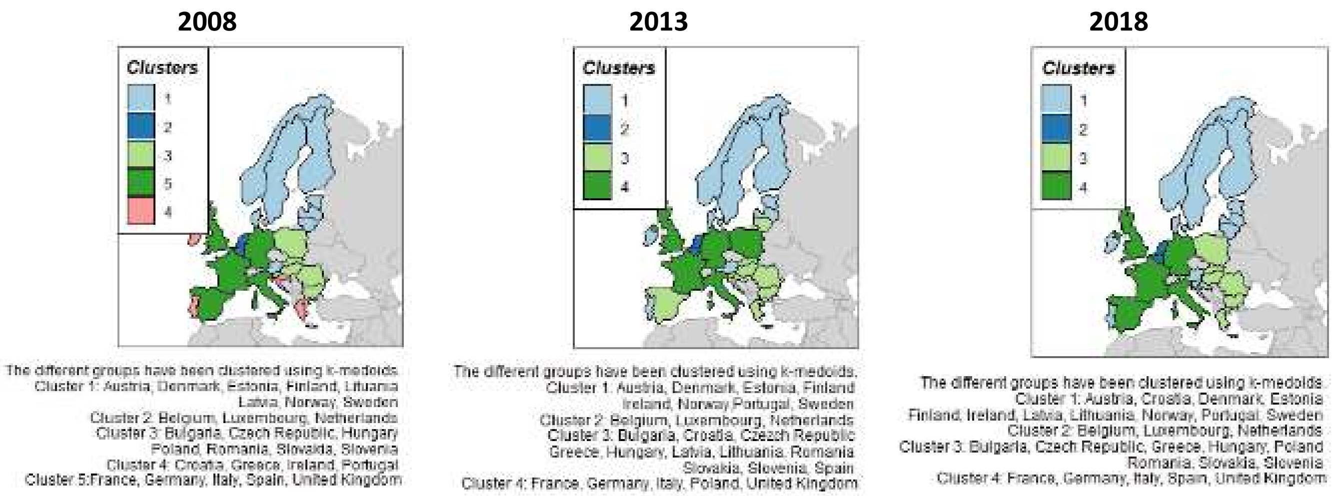
Figure 10 shows the elbow plot for the data on the three reference periods (2008, 2013, 2018). The optimal number of clusters *k* will be chosen whenever more disaggregated groups do not significantly reduce the sum of the squares within clusters. This stands for k = 5 in 2008, k = 4 in 2013 and k = 4 in 2018.

Figure 10 Elbow chart for the three reference periods



The analysis follows with the geographical representations of the clusters for the three reference periods (Figure 11). In this sense, as it was possible to appreciate from the preliminary analysis on the number of clusters, 2013 and 2018 show the same number of clusters. The clustering and the different average performances of countries contribute to creating a diversified picture over the years.

Figure 11 Groups of EU Countries clustered with K-medoids algorithm



From a preliminary overview, there appear to be groups of countries that have been persistent over time for the three different years. On the other hand, over the three years, there have been some changes in the composition of clusters. The analysis will focus on the formation and characteristics of every single year. Figure 12 summarizes the average quantities of the single variables for each cluster.

Figure 12 Average values for every cluster in the three reference years

2008

In Cluster 1 is grouped mostly northern European countries and Austria and Estonia. They are characterized for the highest average performances in terms of clean energy consumption (31 % with respect to 3% of Cluster 2), see Figure 12). This is coupled with the lowest emissions and primary energy consumption. Regarding the socioeconomic variables, Cluster 1 presents relatively high urbanization with low density with the second highest GDP per capita level. Cluster 2 groups Belgium, Luxembourg, and the Netherlands, the richest cluster per number of inhabitants with the highest density. As for environmental performances, Cluster 2 holds the second-highest share of emissions and the lowest share of renewable energies. Cluster 3 gathers all the Balkan, Baltic, and Eastern European States except Croatia and Estonia. This Cluster presents lower socioeconomic conditions and a higher density of inhabitants (105 people/sq meter on average see Figure 12). Those countries present the highest share of solid fuels employed in electricity production (43%, see Figure 12) and relatively low environmental pressure. On the other hand, the Cluster presents a relatively high performance in clean energy production (11% as opposed to 3% of Cluster 2) and energy efficiency. Croatia, along with Greece, Ireland, Portugal, form Cluster 4. This group displays the highest urbanization level (37%, see Figure 12) but the lowest density and number of inhabitants on average. From the energy side, it is the cluster with the second-highest share of renewables in the energy mix (14%). Still, it holds the highest shares of solid and liquid fossil fuels in electricity production (28% and 11%, respectively). Cluster 5 collects France, Germany, Italy, Spain, Poland with the highest share of carbon dioxide emissions on average. The cluster shows the highest energy consumption and the second-lowest share of renewables. It is the most populated cluster with relatively low urbanization but high density. Cluster 4 presents the higher share of manufacturing GVA in GDP.

2013

Cluster 1 groups the same countries as in 2008 with the addition of Ireland and Portugal (Figure 11). In fact, in 2013, the cluster maintained the same position as the best performer in energy consumed from renewable sources. The cluster shows the highest level of urbanization (33%, see Figure 12) the lowest density (59 inhabitants/sq km). Cluster 2 has not changed in composition from the previous. Inhabitants in those countries are the wealthiest, with the lowest share of clean energy. The cluster also presents the second-worst performance in terms of environmental pressure (e.g., CO_2 emissions). Cluster 3 (Bulgaria, Croatia, Czech Republic, Greece, Hungary, Romania, Latvia, Lithuania, Slovak, Slovenia, Spain) holds the lowest wealth per capita and the second-highest share of solid fuels in electricity production (25%, see Figure 12). On the other hand, the cluster presents relatively low carbon dioxide emissions coupled with a sustained share of renewable energies (18%). Cluster 4 in 2013 includes France, Germany, Italy, Poland, United Kingdom. It shows the highest level of emissions with the highest level of primary energy consumption. Furthermore, Cluster 4 holds the highest share of electricity production from (solid) fossil fuels (37% see Figure 12). It also appears to be the highest populated cluster despite the relatively low level of urbanization.

2018

Cluster 1 keeps all the countries as in 2013 with Croatia, Latvia, and Lithuania. It is the least populated, also in terms of density. This group of Countries is the second wealthy cluster in terms of GDP per capita. Moreover, Cluster 1 is the lowest emitter of carbon dioxide in the atmosphere and the highest energy consumer from renewable sources. Despite the relatively high contribution of the industrial sector, the cluster appears to consume a quite low quantity of energy (e.g., Primary Energy Consumption). Cluster 2 (Belgium, the Netherlands, Luxembourg) represents the wealthiest and the most densely populated agglomeration of EU States. On the other hand, it holds the lowest share of renewables (8% Figure 12) and a low industrial productivity level. Cluster 3 gathers Bulgaria, Czech Republic, Greece, Hungary, Romania, Slovak, Slovenia. It holds the lowest GDP per inhabitant but the highest share of industry's contribution to the GDP (21% see Figure 12). On average, 17% of people live in the biggest cities, and the primary energy consumption is the lowest with respect to the other clusters. Cluster 3 holds the highest share of electricity production from (solid and liquid) fossil fuels, reaching 34% of electricity produced in 2018. On the other hand, this cluster shows 33% of energy coming from renewable sources (the highest percentage, 38%, pertains to Cluster 1). Cluster 4 groups France, Germany, Italy, Spain, and the United Kingdom with the highest population level on average. The cluster appears to be the highest emitter of CO_2 in the atmosphere and the highest energy consumer. Despite the highest population level, this cluster shows relatively low levels of both density and urbanization.

Discussion

The analysis of the clusters has identified groups of countries with peculiar characteristics. In this sense, Cluster 1 has always gathered countries that have shown relatively good performance in clean energy consumption, energy efficiency, and carbon dioxide emissions. Countries in that cluster have always been characterised by not being higher populated or densely inhabited. The solid basis of the cluster has been represented by Nordic countries with similar socioeconomic, cultural, and demographic characteristics Blindheim (2015). Austria shares the same performances, whereas it holds a higher population density due to the physical territorial extension of the States. Latvia and Lithuania were present in 2008 and 2018. On the other hand, Croatia, Ireland, and Portugal joined Cluster 1 in 2018. Latvia has shown an increasing share of renewables and relatively low energy consumption patterns. The Investment and Development Agency of Latvia (2020) reported that the Country is now in third place among the EU countries regarding renewable energy consumption. Together with Estonia and Lithuania, those two Baltic countries have shown good renewable production and consumption performances. The favourable climatic condition also helped Latvia, whereas Estonia still appears to be highly dependent on carbon-based energy (Štreimikiene et al., 2016). Croatia managed to increase its overall energy efficiency by 21.4% in the period 2000-2018, mostly led by industry (+ 2.4% per year) and the residential sector (+1.4% per year) (Odyssee ,2021). As for Portugal, Østergaard et al. (2014) observe the Country has used a progressively consistent amount of renewables in the energy mix with the help of favourable climatic conditions to combat energy dependence. Ireland represents the latest newcomer to the Cluster in this picture in terms of (clean) energy performances. Although the share of renewables in consumption has increased over time (4% in 2008, 13% in 2013, 10.88% in 2018), it is still the lowest share. However, energy consumption patterns appear to be in line with the other countries of the cluster. Cluster 2 has been stable for all the periods considered with Belgium, Luxembourg, and the Netherlands. As already disentangled, those countries share the same socioeconomic characteristics with high per capita wealth and a relatively small territorial extension. Indeed, countries in the cluster appear to be the most densely populated. As for energy performances, Cluster 2 shows the smallest share of renewables yet with an increasing trend (up to 8.6% on average in 2018). Quantities of energy consumption have slightly decreased over time along with industrial performances. In 2008 there was also the formation of Cluster 4 with Croatia, Greece, Ireland, Portugal. Greece joined Cluster 3 in 2013 and has not moved since then. On the other hand, Croatia, Ireland, Portugal have joined Cluster 1 since 2013. Newcomers in Cluster 1 in 2018 are mostly related to increasing clean energy consumption and performance efficiency. As already argued, Cluster 3 shows lower economic wealth per capita with an increasing level of urbanization. The cluster also presents a low level of primary energy consumption coupled with lower carbon dioxide levels from fuel combustion. According to the estimates by World Energy Council and Oliver Wyman (2020), Romania scores among the countries with the highest capacity of meeting energy demand internally (e.g., energy security). However, Romania still benefits from being an oil producer while it is still in the process of applying the EU energy agenda. In this sense, in the past two decades, the share of fossil fuel in the energy supply in the country has decreased and replaced with renewables (+10% within 2000-2018) and nuclear power (+5-6% within 2000-2018) (World Energy Council and Oliver Wyman, 2020). In Hungary, the share of nuclear energy accounted for 37% of total final consumption (TFC) in 2015, thus covering the decrease in fossil fuels[13] IEA (2017b). As for Greece, the country has heavily relied on coal (i.e., lignite) production and imports of oil with a small but increasing share of renewables (mostly biofuel and waste) (IEA, 2017a). Reports by Agency of Energy (2019); Ministry of Environment (2018) show Slovenia and Slovakia can be classified as net energy importers with a high share of nuclear power in internal generation. Poland has changed position from Cluster 3 in 2008 and 2018 to Cluster 4 in 2013. Poland has heavily relied on fossil fuel, especially coal, for its energy mix (74.4% of electricity generation from coal in 2020) (Hasterok et al., 2021). Despite the pressing influence of the EU environmental objective of a net-zero economy by 2050, the Polish government still plans to rely on fossil fuels for a long time (Kudełko, 2021). However, according to Polish Ministry of Climate and Environment (2021), Poland will be introducing nuclear power plants in its energy mix by the third decade of 2000 to lower the incidence of coal sources. The position in the cluster with Germany, France, Italy, United Kingdom has probably been achieved due to their bad performances in terms of emissions and clean energy consumption relative to the size of the economy.

France, Germany, Italy, United Kingdom have formed another stable bloc of countries over time. In 2008 and 2018, those four countries were joined by Spain. In 2013 Spain was replaced by Poland in the cluster. This replacement is mainly related to the 2008 economic crisis that particularly hit the Spanish economy in 2013[14]. Countries of this group have scored marked (worse) environmental performances with higher CO_2 emissions coupled with a high population level. From the energy side, Countries in clusters 4-5 show higher energy

[13] In 2015 the country has gone from self-sufficient to being dependent for 87% on imports of natural gas. The same share stands for crude oil. However, the country still relies on coal for two-thirds of TFC

[14] https://www.expansion.com/2013/12/18/economia/1387360918.html

consumption and relatively low but increasing performances in renewable consumption (from an average of 9% in 2008 to 15% in 2018). Despite this higher energy consumption with respect to the other Countries, this cluster shows average industrial sector performance levels over time. However, Alola et al. (2019) proved that carbon dioxide and housing positively impact renewable energy generation in the long run, especially for Mediterranean countries. The cluster contains the most developed economies of the Union, and despite their commitment to EU objectives, they still appear to lag in clean energy generation. According to Telli et al. (2021), the reason can be tracked down to the lack of available space to implement renewable energy generation for the national demand for energy or reliance on other sources for energy production (e.g., France, Spain). Indeed, despite the high commitment of Germany, the country still heavily relies on fossil fuels for energy supply (80% of primary energy supply in 2018). In contrast, for France, nuclear energy contributed 46.6% in 2015 (IEA 2016a, 2020). According to the latest data by IEA (2021a), nuclear energy covers around 45% of production in Spain. The case of Italy[15] is different with an increase in production due to renewable energies (68% in 2015) despite total energy supply still heavily relying on fossil fuels (IEA 2016b).

Conclusions

Since the beginning of the European Union, the so-called harmonization process has paved the way to a common orientation for the Member States, leaving broad discretion to each national regulatory framework (Majone 2014). The EU regulatory framework is one of the most stringent and comprehensive globally. The Union is among the leaders and signatories of many international agreements (Paris Agreement, COP on Climate Change, COP on Biodiversity). In this framework, the latest roadmap at the policy level, the EU has committed to reaching net-zero carbon emissions by 2050 agenda series of other objectives for clean energy, energy efficiency, biodiversity, ecosystem conservation, sustainable production, and consumption (EU Green Deal). This overall (financial and non) impulse will ideally improve Member States' commitments and environmental performances. Ideally, the European Union should act as a cohesive entity in the international landscape. Cultural and historical differences also mark consistent divergences within the Member States regarding environmental policies and the overall orientation of the EU (Jehlička and Tickle 2004). Applying a data-driven approach, this work tries to provide a comprehensive picture of how the Member States are coping with their environmental commitments applying a consolidated analytical framework. The IPAT relationship provided an overarching analytical setting to assess environmental performances comprising social, technological, and economic aspects. However, cluster analysis is highly dependent on the choice of the data to feed the algorithm. This work has focused on those variables that have been traditionally employed in the analysis of the IPAT identity in the literature. The choice of this approach was to provide a framework to the convergence of EU policy that comprises all the relevant dimensions (i.e., economic, demographic, environmental). Further expansions of the analysis may envision a set of variables more in line with the EU's objectives in terms of the low-carbon transition. A clustering algorithm has been applied to three cross-sections of data on three different periods (2008,2013,2018). The analysis identified three specific groups with marked differences: the ones with higher performances in terms of clean energy, energy efficiency; wealthy countries with poor environmental performances instead of relatively poorer countries with promising environmental performances. Among those polarized clusters, some countries have moved through clusters. After a transition phase (2013) in 2018, Latvia, Lithuania joined the cluster of best environmental performers. Croatia, Ireland, Portugal managed to reach Cluster 1 in 2018. On the other hand, Poland joined the cluster of bad environmental performers in 2013. On the other hand, Spain joined France, Germany, Italy, and the United Kingdom in 2008 and 2018. What marks a consistent divergence with the other clusters is the demographic (P) dimension. Even though clustering does not allow for causal relationships, it is possible to affirm that population size plays a consistent role in a country's environmental

[15] Following the results of the referendum in 1987 the Country decommissioned all the nuclear power stations abolishing nuclear energy from its energy mix.

performance. The bulk of the policy framework at the EU level on air emissions and energy efficiency addresses heavy polluting industrial sectors (e.g., energy, petrochemical, industry). On the other hand, residential heating and cooling represent 46% of the total energy consumption for heating and cooling[16] (IEA 2021b). The EU Directive 2012/27/EU (e.g., Energy Efficiency Directive) implements specific measures to promote a precise account of energy consumption related to heating and cooling within (non-)residential buildings meeting the overall energy efficiency targets at the EU level. In this sense, despite all the incentives to promote a more renewable-oriented mix for heating and cooling (e.g., building energy codes), this energy consumption side is overlooked in the environmental policy framework according to IEA (2021b). Barriers to implementing that kind of clean technologies in (non-) residential buildings can be tracked down to the difficulty of the payback mechanism the difficulty of reaching an agreement on the investment (i.e., residential buildings). On the other hand, Fraunhofer Institute for Systems and Innovation Research et al. (2017) find investments for non-residential buildings often are undertaken if they provide concrete advantages in labour productivity (e.g., a better work environment for employees). In fact, of all European Member States, only Croatia has not set specific policy options for heating and cooling in any sector (REN21, 2021). Another interesting emerging pattern is nuclear energy within the energy mix as a substitute for fossil fuel-based sources. Nuclear power represents more than 50% of electricity consumption in France, Slovak, and Hungary and is a higher low-carbon source for other EU Countries (IEA, 2019a). Nuclear power is still under consideration to be included in a Delegated Act of the EU Taxonomy. Indeed, it has been argued that the technology meets the "do-no-significant-harm" (DNSH) principle. European Commission Joint Research Center (2021); Scientific Committee on Health, Environmental and Emerging Risks (2021); IAEA (2021) highlight the main critical points revolve around (hazardous) waste production and material efficiency of existing plants in the use of uranium[17], considering its extraction and the rather insufficient attention to the impact of radiation on (marine) ecosystems.

Overall, Chapter 2 tries to shed light on the state of convergence of national patterns in environmental policy implementation, meeting the objectives at the EU level. Moreover, the work tries to provide a new perspective of employment of a well-established analytical framework. Clustering techniques allow systematization and classification via a sole data-driven approach without any inference on the relationship among variables. Furthermore, the results of cluster analyses are highly dependent on the number and nature of the variables considered. Despite those limitations, the work feeds the literature of policy convergence, providing a systematic classification of countries with respect to their performances in relevant areas of policy intervention. The comparative static analysis over three reference periods provided a diverse picture of environmental performance. The choice of the data has primarily followed the literature on IPAT analysis to provide an analytical framework encompassing all the dimensions of the human-environmental relationship (i.e., economic, demographic, technological, environmental). Further development of this work might include variables more directly related to the objectives set at the EU level on low-carbon transition. Overall, the landscape of the EU Member States presents persistent clusters of Countries over time, also considering the socioeconomic dimension. In fact, after a transition phase (for most of the States in 2013), some Countries managed to increase their performances in terms of clean energy consumption, emission reduction, energy efficiency, whereas some others did not. Ideally, the ultimate aim of the European Union would be to harmonize the Member States in terms of policymaking and (environmental) outcomes; the analysis suggests much work has already been done, whereas much more is needed.

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[16] 72% of energy consumption for heating and cooling comes from coal sources IEA (2021b)

[17] The current technology of nuclear plants implies a high percentage of activated uranium not recyclable. Recent technological development (e.g., *fast-neutron spectrum*) will imply the exploitation of the material 50 times higher than the current rate (European Commission Joint Research Center, 2021)

Chapter 3 - Financial Innovations for Sustainable Finance: an exploratory research

Abstract

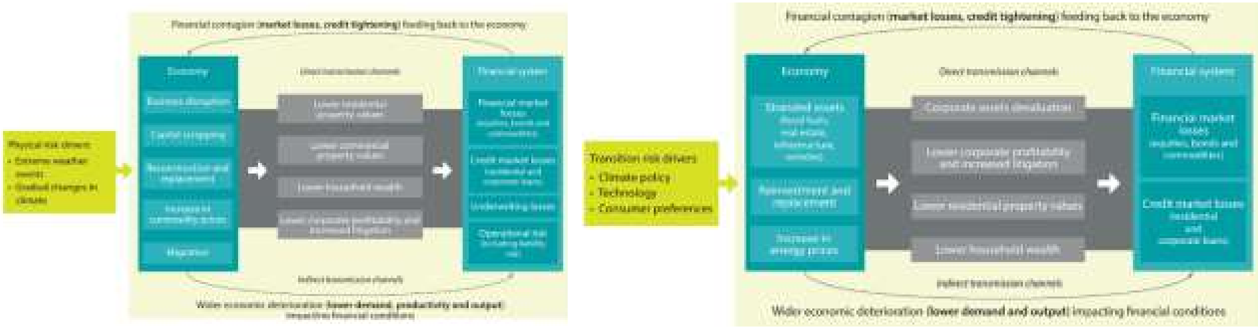
Open climate and green finance issues concern the lack of a comprehensive taxonomy of green and brown assets and the uncertainty over the substantial advantage in investing in green projects (e.g., greenium). Barriers to environmental-related investments boil-down to the lack of a stable climate policy framework coupled with the lack of knowledge about climate change effects, suitable financial instruments, liquidity in the market, and climate-related disclosure. Among this developing framework, financial actors have conceived innovative instruments to overcome some of those barriers in line with the peculiarities of sustainability-oriented investments. Via collecting relevant instances, this work investigates the possible role financial innovations can play in the transition towards sustainability. In some cases, existing structures were adjusted to include environmental-oriented projects extending de-facto their use-of-proceeds (e.g., green securitization, green covered bonds). Some other instruments have been developed, including non-financial dimensions within their pricing models (e.g., weather derivatives). Considering the peculiarities of sustainability-oriented investments, new financial products were designed to merge existing ones (i.e., PRS). New technologies (i.e., blockchain) have improved existing business models favoring alternative ways of financing (i.e., microfinance, crowdfunding) with the pivotal role of public-private initiatives (i.e., Blended Finance, PACE). As the potentialities of financial innovations have been at the core of recent societal turmoil (e.g., 2008 financial crisis), a more cohesive institutional framework could lead to more comprehensive analyses of the effects (positive or negative) they might have on this transition.

Keywords financial innovations; sustainable finance; climate-related risk; sustainability transition

Introduction

So far, Chapters 1 and 2 mainly were focused on carbon markets and policy implementation within the EU framework. As already mentioned in the introduction, the other significant topic of this dissertation is related to the sustainability transition of the financial sector and financial markets. Traditionally, the overall discussion around sustainability transition in finance can be tracked down to the famous speech of Mark Carney (2015), once Governor of the Bank of England in 2015. Carney argued that if environmental economics has been dealing with the tragedy of commons, finance will be facing the "tragedy of the horizon." As widely acknowledged and remarked by IPCC (2018a, 2019), the need for a more sustainable path for society has grown, pressing. According to Spratt (2015); EU HLEG (2018), the financial system and other relevant actors of the economic tissue are called to reconsider its role in light of this overall transition. There are many channels through which the financial sector can play an influential role in boosting a new course of action (Galaz et al., 2018). Indeed, according to Campiglio (2016); D'Orazio and Popoyan (2019); Spencer and Stevenson (2013), the criteria the financial sector adopts to perform this function can be considered relevant towards a consistent shift of the overall societal system. On the other hand, the financial world has been the core of one of the most recent breakdowns of the economic system (The Economist, 2013). The financial system is now under strict surveillance to avoid another economic downturn. The current political discourse focuses more on financial stability, not to mention environmental or social concerns (ACCA, 2011; UNEP FI and CISL, 2014). Indeed, shifting from mainstream finance to sustainable finance entails «deep qualitative changes in the practice of finance», as stated by Lagoarde-Segot (2019). In other words, including sustainability concerns implies the change of the objective of the investment from money to value. Following TCFD (2017); Miller et al. (2019), climate-related risk can be divided into two different categories (e.g., physical, transition risk). Physical risk considers all those risks related to material damage to assets, leading to disruption and loss of value. On the other hand, transition risk concerns the uncertain pathway of the sustainability transition. As the path towards sustainability becomes more concrete, some classes of assets (e.g., fossil fuel) will inevitably lose value with respect to other classes (e.g., renewable sources).

Figure 13 From Physical and Transition risk to Financial Stability risk



Source (Network for Greening the Financial System, 2019)

Figure 13 depicts the mechanism of transmission of climate-related risk to the financial system. Risk stemming from climate change might irreversibly undermine the financial system's stability. Effects on financial assets of physical risk are transmitted to the financial system through losses in the financial, credit, and insurance market due to material disruption or the so-called *stranded assets*. Organizations may be exposed to climate change's uncertain and nonlinear nature (Burke et al., 2015; Miller et al., 2019). If, as found by Miller et al. (2019), the impacts of physical risks can only be quantifiable ex-post, they can hardly be transferable into expected future risks. On the other hand, organizations might be exposed to the framework's continually evolving nature related to a low-carbon transition and the increasing number of litigations. Risks may arise from the uncertainty of technology development and deployment timing and abrupt shifts in commodity supply and demand (TCFD, 2017). Also, there is the issue related to the so-called stranded assets, the loss of value of carbon-related assets due to stricter environmental policies NGFS (2019). Recent works have proved that the portfolios of financial and non-financial institutions are exposed to both those two kinds of risks. Morana and Sbrana (2019) found that 50% of outstanding risk capital in the catastrophe bond market is exposed to Atlantic hurricanes enhanced by global warming. Faiella and Natoli (2018) showed that the augmented hydrogeological risk affects credit lending among Italian firms. Dietz et al. (2016) carried out a study with a version of the DICE model that identified a consistent tail risk for VaR projections in a 2.5 C° scenario.

Indeed, the increasing likelihood of occurrence of harsher climatic conditions along with more stringent policy measures may undermine the correct functioning of financial markets via credit rationing, loss of asset value, illiquidity (NGFS, 2019). On the other hand, Battiston et al. (2019) prove feedback loops transmit climate-related risk from the financial to the economic system. The physical risk may be affecting several aspects of the economy. Expectations of future harshening of climatic conditions (i.e., heatwaves, rising of mean temperature, uncertain rainfall patterns) might induce investors and consumers to save more comprising the adverse effects on the production side for certain more exposed sectors (e.g., agriculture) (see NGFS (2019) and Figure 13). Nordhaus (1977); Tol (2002); M. Burke et al. (2016), among others, have tried to estimate the future losses for the economy (as a percentage of GDP) due to the enhanced physical risk as well as the economic cost of compliance with a low-carbon economy.

The extant research efforts are developing a methodological framework to include climate-related risk within existing credit assessment mechanisms (Battiston et al., 2019). The peculiarities of financial risk related to climate change can be tracked down from the non-linearity of climate shocks, the deep uncertainty on the impact of climate change on human and natural ecosystems, and the endogeneity of risk (Battiston et al., 2019). Moreover, Staubli and Vellacott (2020) notice climate-related risk assessment can only include physical and transition risk, not a combination of the two. This paper will be analyzing the potential role of financial innovations in promoting the sustainability transition of the financial system. Relevant examples are presented after a brief overview of how financial innovations could address structural barriers to investments in the sustainability-oriented project. Those innovative financial appear to be designed considering the structural barriers of the specific area of investment and the institutional framework. However, as the potentialities of financial innovation have led to societal turmoil, a more cohesive institutional framework on sustainable finance is considered a fundamental step for further (empirical) analysis.

A Sustainable Finance Perspective on Financial Innovations

Even though there is a need for further empirical proof, the climate-related risk can affect the overall functioning of the financial system (NGFS,2019). The enhanced risk related to certain extreme events (e.g., floods, hurricanes, heat waves) may directly impact credit restrictions, as Faiella and Natoli (2018) found. Hong et al. (2019) highlighted how the commodity food market underreacts climate-change risk related to the increase of droughts. On the other hand, Clark et al. (2018) find the lack of mandatory disclosures on climate-related risks, "short-terminism" of financial institutions, the imperfect evaluation of natural capital, and the heavy reliance on voluntary commitment are among the main barriers for investments in green-related projects. The most recent data presented in Buchner et al. (2019) show the private sector accounting for 56% of the overall[18] (USD 579 billion) flow of climate finance investments. A systematic study conducted by Hafner et al. (2020) highlighted how the most important barriers to green investments are the lack of a stable climate policy framework and lack of investment opportunities. Other relevant barriers are the lack of knowledge, lack of suitable financial instruments, lack of market liquidity, and lack of climate disclosure. The banking system's role entails the capacity to create credit via expanding both sides of their balance-sheet (Campiglio, 2016). On the other hand, for Best (2017); IEA (2019b), among others, a proactive and well-developed financial system has influenced the energy mix and energy transition. Though, the tendency to disintermediation from long-term credit due to the regulatory framework (e.g., Basel III) and the absence of alternative sources of capital poses and under threat to low-carbon project financing (Spencer and Stevenson, 2013). The Economist (2013); Roncoroni et al. (2017) highlighted asymmetric information, the increasing complexity of the financial network, and the consequent mispricing of assets have undermined the financial system's stability, leading to the financial crisis of 2007. In the aftermath of this most recent economic and financial downturn, the financial realm's policy discourse contributed to redesigning the trade-off between stability and efficiency of the financial system, in favor of the former (ACCA, 2011). In this sense, a study by EBA (2016) finds that the more stringent credit assessment procedures have increased the selectivity of financial institutions. The most recent climate-related stress test by the Central Bank of Netherlands (DNB) and contained in Staubli and Vellacott (2020) highlighted how Dutch banks would lose around 4% points of capital adequacy ratio (10% points of solvency ratio for insurers) due to a climate-related shock for the sole transition risk. Since, according to Basel III regulation, the minimum requirement of that ratio is 4.5%, Dutch banks would fall below the minimum requirement after a single shock. Therefore, financial institutions are demanding politicians set loans of most-sensitive areas of investment (e.g., energy transition) at the lowest risk weighting possible (e.g., lowest capital adequacy requirement) (Kemfert and Schäfer, 2013). As capital and liquidity requirements appear to be marginal in environmental credit risk assessment, stricter requirements at the policy level may generate a trade-off between stability and sustainability (UNEP FI and CISL, 2014). On the other hand, there is increasing concern within academia and policymakers regarding the most appropriate policy framework to foster the transition towards sustainable finance. Indeed, there is wide consensus on the urge of sound and comprehensive definitions for financial activities to proceed further on with the sustainability transition of the financial system (Campiglio, 2016; D'Orazio e Popoyan, 2019b; EUHLEG, 2018; EUTEG, 2020). Another point worth mentioning concerns the debate around the so-called *greenium*, the hypothetical risk premium related to investing in green projects. So far, Alessi et al. (2019) has highlighted how investors are keen to pay a negative risk premium for green

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[18] In 2017/2018 USD 178 billion of loans have been granted to climate-related investments as opposed to USD 675 billion to fossil fuel industry. Green bonds market have increased from USD 65 billion of issuance in 2015/2016 to USD 165 billion in 2017/2018 (Buchner et al., 2019)

assets. In contrast, there exists a threat of potential losses for green vs. brown assets. On the other hand, according to Ambec and Lanoie (2013), IEA (2019), industries focusing on certain environmental aspects (e.g., energy transition) appear to reap benefits in terms of both economic and financial performances. Febi et al. (2018); Zerbib (2017) proved some green-labeled financial instruments (e.g., green bonds) to be more liquid with respect to conventional counterparties. Worldwide, financial institutions and surveillance bodies have endeavored to frame sustainable finance and green activities (for a review, see D'Orazio and Popoyan (2019)). Nevertheless, as broadly argued in Battiston et al. (2019), some financial institutions will soon face a great exposure to climate-related risk. A broad definition conceived in Merton (1992), financial innovations entails those products, processes, and business models conceived to improve the efficiency of the financial system. In this framework, innovations span from technological (e.g., credit card, ATM, Fintech, blockchain) to new sources of access to financial means (e.g., crowdfunding) to financial instruments (e.g., CDO, CDS, securitization). Llewelyn (2009) provide a classification of financial innovations according to their functions. Over the years, many innovative products have been engineered to cope with a specific aspect of financial risk:

Table 4 Summary of Financial Innovative products and their functions

Innovation	**Function**	**Type of risk**
Securitization, Credit/Debit cards	Increase liquidity of specific markets (i.e., real estate)	Liquidity Risk
Credit Default Swaps	Shifting/hedging risks	Credit Risk
Credit Sensitive Notes	Reducing Agency Costs	Operational Risk
Zero-coupon bonds	Deduct interest expenses faster than interests on the bond	Tax Risk
Equity contract note	Convert the notes into the common stock of the bank	Legal and Regulatory Risk

Source (Finnerty, 1992; Gastineau, 1993)

Table 4 depicts a small summary of some innovative financial products, their functions, and the type of risk they try to tackle. Financial innovations, such as securitization, effectively enhance the liquidity of a particular market (e.g., real estate). Credit Default Swap, for instance, is designed to shift risk or hedge investors from the occurrence of a particular credit event that may endanger the possibility of repayment (Amadei et al., 2011). Some engineered financial products are also conceived to reduce transaction and agency costs, such as sensitive credit notes. Furthermore, Llewellyn (2009); Lerner and Tufano (2011) argue that, as in the manufacturing sector, innovations within the financial realm can be triggered either by a specific need of the market or to overcome certain barriers from the regulatory side. There is relatively poor literature on both from the theoretical and empirical point of view (see Frame and White (2004); Lauretta (2018) for a review). However, Allen and Gale (1995); Brunnermeier (2009) consider innovative financial products either as a positive factor fostering the financial system growth (e.g., innovation-growth view) or as a negative factor (e.g., innovation-complexity view) increasing the complexity of the financial network.

After the famous speech by the former governor of the Bank of England, Mark Carney (2015), the financial sector has introd environmental concerns in the financial decision-making process. Especially coming from the public sector and some private initiatives, many instruments used and regulations are now trying to boost the financial realm's sustainability transition and the economy (International Capital Market Association, 2018). In parallel, Chatzitheodorou et al. (2019) state that after increasing attention to climate change and the environment by investors and media, actors in the financial market have developed tailored financial investments solutions (e.g., green bonds, SRI). However, even though climate-related financial risks have been identified, investors are also concerned with the future effects climate change will exert on the diverse aspects of financial risk (Bolton et al., 2020). Uncertainty regarding physical risk is related to the unpredictable effect of the alteration of biogeochemical processes on socio-economic systems coupled with the eventual reaching of the so-called *tipping points*. Transition risk in itself is uncertain due to the possible occurrence of four different scenarios related to the capability of the financial system to cope with the overall societal transition towards sustainability.

While coping with a lack of a comprehensive framework on sustainable finance, financial investors are trying to overcome common barriers and risks related to green and climate-related investments by adopting multiple approaches. In specific sectors (e.g., electricity), the overall policy push highlights the need for increasing investments (Carus, 2013; IEA, 2019b). As mentioned by Best (2017), the role of the financial sector might be pivotal in fostering an overall sustainability transition. Environmental-related investments may include small-scale projects (e.g., private solar panels, energy-efficient houses) or greater infrastructure projects (i.e., wind parks, solar farms, smart grids, water management, hydropower, water infrastructures, green buildings). Breitschopf and Pudlik (2013) argue that the nature of the project bears different layers of risk and a variegate approach to deal with it. On the other hand, the enhanced requirements for accessing credit, sustainability, and solvency of financial institutions might pose additional barriers to investments in the field de (Paiva, 2010). Since the amount of capital at the disposal of specific (high) risk categories of assets might be limited, investors adopt strategies to access this market segment (Barlett, 2019)[19].

State of the art of climate-related financial risk

The perception of risk for investors is reflected in the financing cost (e.g., interest rate) or cost of capital (e.g., return expectation): this is valid either for high or low carbon technologies. Whereas fuel costs primarily drive high-carbon investments, net-zero projects are more capital-intensive (IEA, 2019b; Schmidt, 2014). Low-carbon projects with relatively low abatement costs appear to be affected by a higher level of risk with respect to their fossil fuel-based counterparties. According to Catalano et al. (2020), climate change is liable to affect capital stock erosion via two channels, namely "gradual factors" and "extreme events." The former concerns aspects of climate change with a slow but intensifying economic impact in the future (i.e., crop displacement, sea-level rise). The latter are climate-related phenomena exerting significant impacts on physical assets in a short period (e.g., floods, hurricanes, droughts). Specific projects are highly dependent on climatic conditions (i.e., renewable energy production). The unpredictability of weather might threaten the feasibility of the overall investment. Green projects may also entail expensive high-tech components, extending the investment return period (Taghizadeh-Hesary and Yoshino, 2020). As low-carbon projects involve many actors in the process, a risk assessment should be addressed adopting a multi-stakeholder perspective (Waissbein et al., 2013). In this sense, Criscuolo and Menon (2015) argue a funding gap might be identified for those projects bearing a high technology risk profile even at the seed stage (e.g., renewables).

Renewable energy

The trend for the future will see an increase in investments in the field as a prominent cornerstone of the energy transition. Investments in renewable energy sources may take a long run to be implemented to their full extent. Building on anecdotal evidence, Semieniuklder (2019) highlighted how technologies (i.e., photovoltaics, wind) deployed in the current energy transition represent the endpoint of an innovative process that started decades ago. Unlike fossil fuels, the capital cost is the foremost concern for renewables (May et al., 2017). Despite the overall effort, there seems to be little incentive for certain investments in the field (e.g., smart grid) (IEA, 2019b). Reicher et al. (2017) highlighted that while clean energy projects might face a high-risk profile, the bulk of securities sold annually in the US bond market[20] is low-risk blue-chip investments. The global pension market devotes only 0.01% of total assets to clean energy projects (e.g., green infrastructures). Major financial investors tend to adopt a conservative approach instead of the high-

[19] «only 1 % (or $89 billion) of the $7.3 trillion US bond market is for new high-yield investments». Barlett (2019)

[20] The US public bond counts $7.3 trillion of new issue volume annually, 1/3 of the world bond markets. Though, Furthermore, only $89 billion (2% of the bond market) is destined to new investments (Reicher et al. 2017)

risk nature of investments in renewables. Moreover, the investment gap is more evident in developing economies[21] (e.g., Location Problem) (Reicher et al., 2017). While technological progress has concretely reduced costs for renewable projects, this induces investors to wait and see to what extent prices will further drop in the future (Taghizadeh-Hesary and Yoshino, 2020). Even though levelized costs for clean energy technologies are progressively falling, the upfront cost will likely represent a relevant hurdle for clean energy access, especially in low-income countries (Glemarec, 2012). Investments in renewable energies bear different layers of risks. Salm et al. (2016); Reicher et al. (2017); Barlett (2019) consider that the nature and the importance of those risks have changed over time, and it also depends on the kind of project. Risks may arise from the public sector regarding uncertainties on the (suboptimal) regulatory framework and lack of efficiency in administering permits and licenses. Technological and resource risk affect project developers when dealing with costs, supply chain, infrastructures, and local expertise. Utility companies may face risks related to poor infrastructure management and their credit quality. Risks for investors might arise from country-specific factors (i.e., lack of experience on renewable energy investments, capital scarcity, currency risk, macroeconomic performances) (Waissbein et al., 2013). Risks of investing in renewable energies may arise in different phases of the life of a project (Breitschopf and Pudlik, 2013). Sources of capital to finance renewable projects are debt and equity investments. Equity investors and lenders may adopt different ways to analyze the risk of a project. The former tends to undertake high-risk projects if the (potential) returns are large enough. On the other hand, lenders tend to look at the default risk, and they do not lend whenever there is a consistent likelihood (Wiser and Pickle, 1998). Due to administrative barriers, the planning and development phase involves consistent equity investments, thus risks. Debt capital is the primary funding source during construction, exposing banks to increasing risks since the operational phase (Breitschopf and Pudlik, 2013). The operational phase is when capital debt and default risk start lowering, replaced by other natures of risks. As Mazzucato and Semieniuk (2018) argued, Technological risk comprehends risks regarding some malfunctioning of technical components or technical failures. On the other hand, the energy sector appears to be sensitive to changes in the political climate at the regional level (e.g., micro-political risk) that can undermine the whole endeavour (Lee and Zhong, 2015).

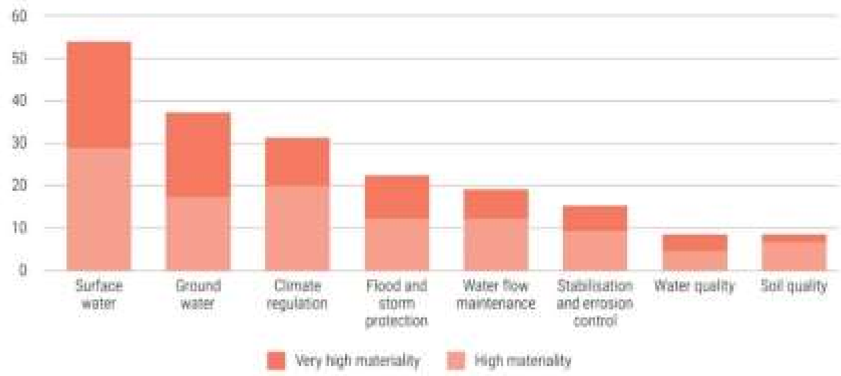
Biodiversity loss and ecosystems disruption

The most recent account of ecosystem service evaluation was calculated in 2011 by Costanza et al. (2014), a monetary value of USD125 trillion per year with a relative loss from 1997 to 2001 of USD 2.3 - 20.2 trillion. In this sense, Dasgupta (2020) considers biodiversity one characteristic of the “asset” ecosystem. Business activities impact ecosystems via consumption, pollution, and land conversion. At the same time, specific kind of activities depends on ecosystems to function. The beverage industry relies on the supply of fresh water, whereas agribusiness on pollination, pest control, erosion, and control services (Hanson et al.,2012). For this reason, the likely degradation of specific ecosystem services might entail risks for businesses (e.g., exposure, vulnerability). Consequences for businesses may, in turn, generate feedback related to their impact and dependency on nature (McCraine et al., 2019). The operational risk might arise from the enhanced cost of freshwater, the lower output of hydroelectricity, or the disruption of coastal businesses due to flooding. Other sources of risk might be generated from the uncertain policy framework with the increase of possible litigations and fees. NGOs might target companies for buying raw materials (i.e., wood) from non-sustainable sources, or they might finance ecosystem-degrading activities (e.g., reputational risk). In this sense, customers may switch to suppliers with a lower impact on ecosystems (i.e., market risk). Indeed, sector biodiversity is already a source of risk for business activities. A particular share of risk is related to the progressive loss of biodiversity (i.e., physical risk). The progressive destruction of the natural environment will eventually disrupt certain supply chains (e.g., fish stock) and enhance the likelihood of occurrence of specific natural hazards (i.e., floods, droughts) (World Economic Forum, 2020). Sources of risk might also

[21] The so-called BRICs (Brazil, Russia and China) Countries accounted for 43% of CO_2 emissions globally in 2015 (Reicher, et al. 2017).

arise from litigations due to breaches of the legal framework related to preventing biodiversity loss (i.e., litigation risk), as stated in Staubli and Vellacott (2020). Another type of risk is related to the exogenous (and endogenous) impact of biodiversity loss on the functioning of the financial system (i.e., systemic risk). Indeed, the financial system may suffer from external biodiversity shocks, or banks may suffer from biodiversity loss. Furthermore, biodiversity loss may exert a reinforcing (second-round) effect exacerbating climate change. Business activities more exposed to natural capital risk pertain to primary sectors such as agriculture, aquaculture, fisheries, forest products. Material dependency on nature is also present in the energy (i.e., hydropower, water utilities, oil, and gas) and mining sector. Figure 14 shows the survey results on 60 enterprises of different business sectors on which ecosystem services are material dependent for those enterprises.

Figure 14 Ecosystem services with material dependency for business sectors



Source (Natural Capital Finance Alliance & UN Environment World Conservation Monitoring Centre, 2018)

As the Figure from Natural Capital Finance Alliance and UN Environment World Conservation Monitoring Centre (2018) shows, the most critical ecosystem services for businesses are those related to the water cycle (e.g., groundwater provision, surface water provision, water-flow maintenance) along with climate regulation and prevention of natural hazards.

Green financial innovations: relevant examples

Given the mounting attention on environmental-related issues, financial players have been conceiving instruments to either shift or lower risks related to climate change. As already stressed, risks may manifest differently to the various stakeholders. For this reason, from both the private and public spheres, there have been many attempts to mitigate this kind of risk by promoting green projects.

Table 5 Summary of tools and instruments to foster sustainable finance

Goals	Functions	Tools and Instruments
Facilitate access to finance/investments	Providing long-term finance/capital Facilitating access to private finance/capital	Equity Investments International climate funds Public-private partnerships Institutional Investors (pension funds, insurance companies, etc.)
Reduce risk	Risk-sharing Credit enhancement mechanism	The green credit guarantee scheme Financial de-risking Policy de-risking Structured finance Public-private partnership

Raise the rate of return	Making green projects feasible	Utilizing the spillover effect in the form of tax refunds to private investors
Increase capacity	Aiding project development Reducing project risk	Technical Assistance Capacity building Information tools (e.g., energy certificate tracking, etc.)

Source (Taghizadeh-Hesary and Yoshino, 2020)

Table 5 summarizes some possible tools and instruments to overcome the most common barriers to fostering green investments. Along with public interventions (e.g., tax refunds, policy de-risking, green credit guarantee, information tools), there are also private initiatives (e.g., financial de-risking, structured finance). Furthermore, public and private cooperation might be useful to overcome specific barriers. In this sense, conceiving new green financial products, risk analysis, and management methodologies require an innovative impulse from the private sector (G20 Green Finance Study Group, 2016). While mitigation efforts are mostly concentrated in developed countries, adaptation investments also involve developing countries (Dellink et al., 2009).

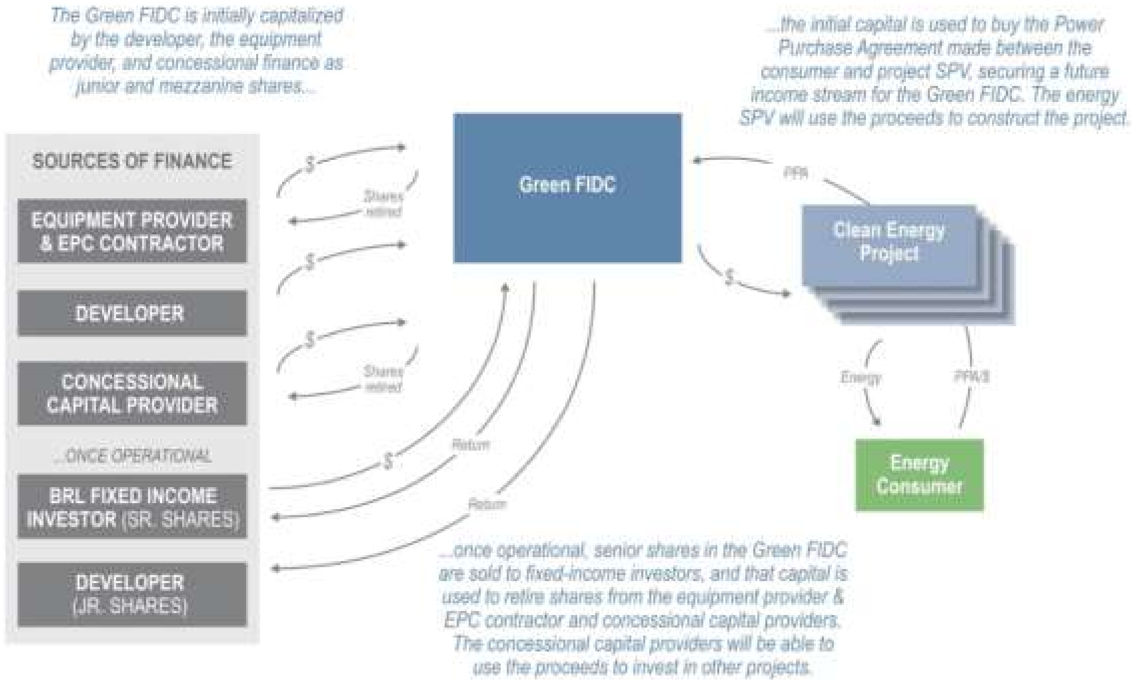
Derivatives

Financial instruments, such as climate derivatives, could be pivotal in shifting risks related to certain kinds of adaptation investments. As the underlying asset is a physical quantity, pricing of weather derivatives follows a different mechanism from conventional ones (Teng Lei, 2012). Little et al. (2015) show how aquaculture companies can hedge sea level rise risk through a European put option based on sea surface temperature forecasts. Bloch et al. (2010) theorized that some climate derivatives (i.e., Climate Default Swap, Climate Default Bond) could virtually distribute risks of sea-level rise among several projects. In this sense, enterprises may partially use those contracts to shift weather-related risk to counterparties. In fact, according to the underlying index (i.e., temperature, wind, rain, snow, or sunshine hours), those instruments can cover various risks related to climate change. The characteristics of these categories of bonds are suited after the specific need to hedge the single enterprise and the risk faced. In exchange for a constant amount, companies call on banks that will eventually pay a premium if the climatic/weather event may occur. The bank, in turn, will issue the (weather) bond to diversify its portfolio (Barrieu and Karoui, 2002). Despite the specific address those instruments cover, they are not much used in contexts exposed to natural disaster risk (Arias, 2013). Derivative instruments are also used to hedge other layers of financial risks. “Long-Term FX Risk Management” provides a set of derivative instruments to shift interest rate and currency risk. As investments in clean technologies require long-term commitment, operational lifetime, and payback, this instrument will hedge those types of risks via issuing derivatives. This business model combines interest rate hedges with cross-currency swaps, allowing to price longer-term FX swaps (Escalante and Frisari, 2018). Local currency loans will be offered to clients as a more appealing way to finance in the frontiers market. The International Finance Corporation (IFC) will underwrite the cross-currency swap and re-hedge its exposure. Proxy Revenue Swaps (PRS) was pioneered by Allianz Risk Transfer with the help of Nephilia Climate and REsurety as an innovative risk-transfer tool for renewable energy investments. Initially conceived for wind farms, it now comprises solar projects (Gamache, 2018). PRS combines two separate contracts, namely proxy generation swap and weather hedge. The former tries to align buyers and sellers in a mutually beneficial agreement secured by this contract. For this reason, the contract is settled according to the power curve, wind measurement, and operational efficiency. Whenever sellers operate more efficiently, they are entitled to retain revenues for the additional power generated. Weather hedges secure a constant revenue flow over the year. In its principles, the hedge provides a fixed amount per quarter without regard to the performances, project volume, and electricity price. On the other hand, the project pays a floating amount (e.g., proxy revenues) as the sum of the proxy revenue for each settlement period in that specific electricity market (Gamache, 2018). In this sense, PRS will secure a constant flow of revenues to fund the project via hedging risk related to the project's performances (e.g., shape risk). Even though the project is designed for small developers to hedge their day-to-day flows, some big players on the market have decided to make use of PRS as a flexible off-take agreement. For instance, Enel Green Power (2019) partially hedged its Lonesome Wind Farm in the USA via issuing PRS for the 295MW portion of the farm. According to some representatives interviewed, the company uses PRS to bring a practical economic value concerning other off-take options.

Green Securitization

Securitization has paved the way for new investment channels and a different approach to loans portfolio management (Buchanan, 2017). In the green finance realm, Climate Bonds Initiative (2015); Sonntag-O'Brien and Usher (2004); Bai and Zhang (2020) argue securitization can help finance small-scale low-carbon investments via shifting risks and easing banks' balance sheets. As many long-term sustainable investments might not match banks' capital deposits and balance-sheet, securitization might be the tool enabling the potentialities of the private sector to low-carbon projects (Legenchuk et al., 2020). According to Hussain (2013), some advantages of this procedure are that it is possible to free-up funds and aggregate several projects via issuing bonds secured by multiple sustainable projects. Governmental governments' securitization might be less likely constrained by fiscal budgets (OECD, 2016a). Climate Bonds Initiative (2018) notices securitizing green projects can either mean the underlying cash flow related to low-carbon assets or the proceeds for the loan are earmarked green assets. When issuing Asset-Backed Securities (ABS), investors (and policymakers) should take into account the formation of asset pools, the process of asset evaluation, the purchase of the asset by uncertain investors (Alafita and Pearce, 2014). In this sense, ABS is composed of different tranches according to the riskiness of the asset in each level (e.g., waterfall distribution, see Krupa and Harvey (2017)). According to the risk layers, tranches can be accessed by several different investors. Therefore, via tranches, it is possible to create new classes of risk that can be traded in the market (Lee and Zhong, 2015). Also, the risks of ABS will be adjusted as technologies mature without assessing the risk of the single project OECD (2016a). Lam and Law (2018) found securitization of certain loans is an established practice to finance renewable energies projects in developed countries and a potential source of financing in developing economies. For instance, the Solar Securitization for Rwanda promotes sustainable energy access via securitizing pools of loans from multiple companies to finance solar projects in Rwanda (Borschiver and Lonsdale, 2019). This instrument has been conceived to aggregate multiple small-scale projects and channel private capitals in a relatively challenging market such as the African one. In 2017 Crédit Agricole performed the first issuance of a green synthetic securitization of around US$8.2 billion of risk transfer. With this operation, Crédit Agricole managed to free up around US$2 billion of new lending opportunities in the field of renewables, energy efficiency, building renovations, sustainable waste. Unlike the traditional procedure, synthetic securitization is the sole risk to be transferred via derivatives, while ownership of the securitized exposure remains with the originator (Angelos, 2016). On the other hand, "Green FIDC" builds on an existing legal framework for securitization in Brazil (e.g., Fundo de Investimento en Direitos Créditorios). This close-ended fund will be raising capital via issuing different classes of shares. Figure 15 shows a simplified version of the mechanism as in Escalante et al. (2017)

Figure 15 Operating principle of Green FIDC



Source (Escalante et al., 2017)

In the pre-operational phase of the project, the FIDC will be capitalized by the developers and equipment providers of energy efficiency or renewables projects. The fund will acquire receivables from Power Purchase Agreements (PPAs) via a Special Purpose Vehicle (SPV) against an energy off-taker. In this way, the fund will finance the project and deliver energy to the off-taker. The FIDC will issue senior shares to fixed-income investors in the operational phase, retiring the (junior) shares from the equipment providers. The funds to pay senior and junior shares will come from off-takers as a payment for the energy.

A specific kind of ABS is backed from interests paid for loans (e.g., residential mortgage-backed securities). Fannie Mae (2019) is one of the most important issuers of Green Residential Mortgage-backed Securities (RMBS), with US$ 20.1 billion in 2018. Fannie Mae's Single-Family Green Mortgage-Backed Security (MBS) includes only mortgages of single-family residential homes that exceed national standards in energy efficiency[22]. In Europe, Obvion (2020) issued the first green RMBS in 2016 for € 526.6 million.

Green covered bond

Covered bonds are securities collateralized against a pool of assets. In case of failure, those assets can cover claims at any time. Collaterals might be mortgages, the public sector, or ship assets (EMF-ECBC, 2020). Unlike ABS, the cover loans remain in the issuer's balance sheet, coupons and payments are established in advance (e.g., no-prepayment risk), the pool of assets is allowed under strict legal requirements, and borrowers are liable with all their assets (Prokopczuk et al., 2013). Damerow et al. (2012); Ketterer et al. (2019) infer those instruments are used to create liquid assets with a lower funding cost and risk and adjusted for low-carbon initiatives. Green-covered bonds can count on stable cash flow from the (green) asset pool, making them perfect collaterals and minimal portfolio adjustments (Ketterer et al., 2019). As there is still no shared definition of green assets, the first green-covered bond proceeds were mainly related to energy-efficient buildings (e.g., mortgage covered bonds) and finance community projects in the healthcare and education sector (EMF-ECBC 2020). In 2018, as Gramegna (2018) reported, Luxembourg introduced a legislative framework for renewable energy-covered bonds. This new category was issued for the first time in early 2020

[22] The certification is provided by ENERGY STAR

from Luxembourg, extending de-facto the proceeds of covered bonds and renewables (EMF-ECBC, 2020). The legal framework of the instruments has been conceived to increase the financing of renewable projects. In this sense, loans underlying the covered bonds may also include acquiring instruments from a securitization company (or a compartment) with at least 90% of assets in renewables or if the proceeds of the issue are used for at least 50% to refinance assets generating renewable energies. Also, derivatives instruments may be used to guarantee the overall coverage of the covered bonds (Lovells, 2019).

Blockchain

Despite some limitations studied by Krause et al. (2016), among others, Distributed Ledger Technology (DLT) (e.g., blockchain) provides security, transparency, decentralization, lower costs (i.e., no need for banking infrastructure), and higher speed (internet-based) for financial operations. The flexibility of this technology allows blockchain to be applied to different fields, including finance and financial services (Priem, 2020). Indeed, blockchain technology characteristics also appear to be a perfect fit for boosting sustainable finance use of proceeds (Bayat-Renoux and van der Lugt, 2018). According to Micale and Van Caenegem (2019); Singh et al. (2020), blockchain technology provides a secure infrastructure to foster aggregation and access to financial services to the most sensitive categories. Blockchain Climate Risk Crop Insurance has created a platform for smallholder farmers in Kenya to provide automatic insurance coverage. The platform provides a flexible and secure instrument to match demand with the supply of insurance. Farmers are quite exposed to climate change and in need of insurance coverage that could ideally be enabled right after the disastrous event. On the other hand, insurance enterprises require quality data and lower transaction costs ensured by smart contracts via DLT (Micale and Van Caenegem, 2019). GROVE: Forestry Smart Ledger (FSL) is another blockchain-backed peer-to-peer (P2P) infrastructure with the aim of funding community mangrove projects with the highest impact possible. In the overall mechanics of the platform, DLT ensures traceability, transparency, security, and disintermediated financing for the projects. Those initiatives have the multiple purposes of improving carbon sinks sites while benefiting local coastal communities (Singh et al., 2020). Green Asset Wallet (GWA) (2020) is another platform that benefits from blockchain technology. GWA provides a secure, transparent, and reliable environment to three categories of financial agents. Issuers can supply the platform with essential information on their green bonds certified by validators. Investors will create their portfolios and monitor their performances. EPC Blockchain is a distributed-ledger-based platform to create a consortium (Blockchain Energy Savings Consortium) investing in renewable energy sources and helping monetize carbon offset credits (BESC, 2020). Blockchain-based cryptocurrencies have also been implemented, empowering communities towards more sustainable behaviors (i.e., GreenBit), incentivizing investments in specific sectors (i.e., Solarcoin[23]), promoting and monetizing carbon offsetting (Climatecoin[24]).

Private and Public Partnerships

Convergence (2020) and OECD (2019) define blended finance as all those efforts from public and philanthropic entities to impulse private investments in areas related to the Sustainable Development Goals (SDGs). Blended Finance initiatives are more oriented towards developing economies through different forms of intervention. They might provide capital at a below-market cost (concessional debt or equity), ensure guarantees for credit enhancement to particular initiatives, facilitate investments in the utilization of the funds (i.e., technical assistance fund), or the design of the transaction (Convergence, 2020). In other terms, Conservation Finance Alliance (2020); Mawdsley (2018) framed blended finance as the combination of financing instruments with different risk/return profiles catalysing investments. While philanthropic organizations may endure lower returns accepting higher risk, blended finance vehicles can use diverse sources to finance companies (Conservation Finance Alliance, 2020); Convergence, 2020). This can be

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[23] https://solarcoin.org/

[24] https://thebitcoinnews.com/climatecoin-2/

translated into long-term sources of funding provided to early-stage businesses. The latest data collected in Convergence (2020) show equity represents 33% of the overall investments while MSMEs and small and growing businesses jointly represent more than 40% of the overall funds channeled. The peculiar structure of blended finance vehicles can promote the implementation of debt conversion mechanisms (e.g., debt-to-nature swaps) (Blue Bonds for debt conversion in Small Island Developing States), can design incubators for local businesses (ACELI Africa, Sustainable Seafood Fund), can catalyse climate-aligned finance[25]. Property Assessed Clean Energy (PACE) is a public-backed program allowing property owners to finance upfront energy retrofit costs paying back via a voluntary scheme. The mechanism is based on an existing structure known as a "land-secured financing district" attaching the loan to the property rather than the owner (California Debt and Investment Advisory Commission, 2008). Each loan will take the property as collateral and a "super-priority" first-lien over all the other lien holders (Federal Housing Finance Agency, 2020). PACE is a well-established practice in some US States (i.e., California), though similar programmes occur in Europe[26].

Microfinance and crowdfunding

As regulations and credit assessment have become more stringent, some most sensitive categories (i.e., start-ups, SMEs) are recurring to alternative means to gather starting funds. In this sense, Mollick (2014); Cavallito et al. (2017); O'Reilly (2007) state microcredit and crowdfunding represents two participative business models for entrepreneurs and small businesses to access some forms of financing. A more active role of the investors and a business model more sustainability-oriented effectively allows credit to categories otherwise excluded from traditional financial channels (Yunus et al., 2010; Pronti and Pagliarino, 2019; Conservation Finance Alliance, 2020). Furthermore, in some cases, Conservation Finance Alliance (2020); Sorenson et al. (2016); Vismara (2019) found that sustainability-oriented business models might be perceived as a guarantee of the success of the investment. Following the review by García-Pérez et al. (2020), microfinance initiatives have specialized in various dimensions of sustainability. Aspects more strictly related to the environmental concern, adaptation investments (i.e., natural disaster prevention) in sectors more exposed to the effects of climate change (i.e., agriculture) and access to clean energy (Convergences, 2019; Oikocredit, 2020). CAMBio (2013) is an initiative that has taken place in Latin America to enable investments in the conservation of biodiversity for SMEs via microfinance (see also Forcella and Lucheschi (2016)). Oikocredit (2020) has piloted a programme in the Philippines on Natural Disaster Management. Partner Microcredit Foundation has launched a project to foster energy efficiency in Bosnia-Herzegovina (European Microfinance Network, 2013). Crowdfunding platform Kiva.org has raised a quite lively interest in academia (see Choo et al. (2014); Flannery (2007); Hartley (2010) among others) as one prominent instance of a high-impact crowdfunding platform. According to Hartley (2010), its peculiar business model (i.e., Kiva Protocol[27]) allows the platform to fund ventures that might be considered too risky for the industry. Among many ventures, the platform has funded Komaza in Kenya to help smallholder farmers convert drylands into small-scale forests to tackle desertification and provide a more sustainable wood supply chain (Komaza). Gofundme.com raises around €45 million of funds for ventures related to the environment[28]. Fridays For Future (FFF) has also used the platform to finance their campaigns[29]. In the field of renewable energies, the EU-funded project "CrowdFundRES" identifies four case studies (Oneplanetcrowd, Lumo, CONDA, Bettervest) of crowdfunding platforms funding projects on residential energy efficiency, renewable sources, biomass Maidonis (2018).

[25] (*Aligned Intermediary Awarded Grant to Support Climate Finance Partnership - Press Release - Convergence News | Convergence*, 2020; *Design of the Local Utility Project Aggregator (LUPA) - Design Funding | Convergence*, 2020)

[26] For a deeper insight see https://www.europace2020.eu/

[27] The so-called *Kiva Protocol* has been used in Sierra-Leone to build the first National Identity Platform (kiva.org, 2019)

[28] https://www.gofundme.com/start/environment-fundraising

[29] https://www.gofundme.com/f/fridaysforfuture

Discussion and Conclusions

This Chapter has been conceived with a twofold aim. It provided a brief overview of the most emergent issues concerning the sustainability transition of the financial sector. On the other hand, it hypothesized a possible role of financial innovations tackling specific classes of risk related to sustainability-oriented investment and climate change. As the effects of climate-related risks have been disentangled in details (e.g., transition risk, physical risk), financial players are still struggling to introduce those layers of risk in their credit assessment mechanism. Despite the extant efforts (i.e., EU TLEG), the institutional framework on sustainable finance appears not to provide sound working principles to proceed with the sustainability transition. More stringent regulations, the lack of a comprehensive (and mandatory) institutional framework, and short-terminism are the main barriers to investments in the most sensitive sustainability transition areas (i.e., renewable energies, biodiversity, and residential energy efficiency). Furthermore, there is no systematic proof of a premium (so-called *greenium*) for sustainability-oriented investments. In this sense, the function of financial innovations may be able to overcome some of those barriers. In its broader definition, financial innovations encompass products, processes, business models designed to improve the efficiency of the financial system via tackling some specific layers of risk. Given the peculiarities of sustainability-oriented sensitive areas, financial innovative instruments have been conceived tackling specific aspects (e.g., risks) related to those kinds of projects. The analysis of relevant instances of financial innovations specifically addressed to sustainability-oriented projects highlighted different innovative efforts and common traits. In some cases, existing structures have been adjusted to the specific peculiarities of green investments (i.e., green securitization), also considering specific regional cases (e.g., Green FIDC) or area of investments (e.g., Green RMBS). On the other hand, some instruments merely extended their use-of-proceeds to a specific area of investments (i.e., green covered bonds). It is also possible to identify modular, innovative financial instruments, such as weather derivatives, where the index-based instrument has been substituted with climate and physical indexes (e.g., temperature, sea-level rise). Some instruments were also conceived, merging two or more existing structures (i.e., PRS, Long-term FX Risk Management) providing a better fit to the specific needs of the sector. In digital applications, new technologies have been applied mostly to risk management and financial services. The use of blockchain ensures traceability, transparency, reliability, and disintermediation. New technologies might have the potentialities to overcome financial exclusion for some sensitive categories. As in crowdfunding, all the platforms finance with success MSMEs, start-ups in sustainability-related ventures. On the other hand, some emergent business models (i.e., microfinance) try to couple non-financial (e.g., poverty exclusion, financial inclusion) values with reliable returns for investors. In this landscape, the role of public/philanthropic organizations in boosting private sector investments (e.g., Blended Finance, PACE) has been consistent in specific contexts. This overview has presented a series of use-cases of innovative financial efforts to align the financial system with sustainability. Furthermore, some structural gaps in the field have been highlighted that seem to undermine a more cohesive transition. The major barrier is the lack of concrete proof of an advantage for investing in sustainability-oriented projects, despite the overall research efforts (Alessi et al., 2019; Biasin et al., 2019). In addition, the consistent efforts to set an institutional framework appear to be still in their infancy, providing uncertainty for financial players. In this context, the private sector is coping with those structural barriers also pushed by the investors that require more conscientious investments and investment evaluations. Besides some voluntary regulatory frameworks (i.e., Equator Principles, ICMA- Green Bond Principles, CBI- Green Bond Certificate), financial players have come up with some innovative instruments trying to couple the needs of the investors, the peculiarities of the sector, and the lack of institutional framework. Despite the consistent lack of contributions in the field of financial innovations Frame and White (2004); Lauretta (2018) this work can be considered an ulterior systematization in light of the repercussions they have had with respect to some recent events The Economist (2013). This study represents an exploratory incursion in a growing topic of an early-stage field of study with substantial potentialities. Starting from the regulatory framework of sustainability-oriented financial innovations aiming to create the most suitable environment for innovations without undermining the financial sector's stability. In Europe, as exposed in European Securities and

Markets Authority (2020), a new regulation[30] for securitization will strengthen the disclosure requirements for securitization opening to environmental concerns. On the other hand, some solutions have been proposed considering the peculiarities of technological, financial innovations (i.e., regulatory sandbox) with the potential to include sustainability concerns (FCA, 2015). In this respect, the non-financial reporting directive (2014/95/EU) is another instance of regulatory efforts nudging the financial system towards sustainability. By all means, a comprehensive framework is at the basis for further (empirical) research on the *greenium* matter in a field where "green labels" to investments are prerogative of non-profit initiatives (e.g., CBI, CICERO). As the potentialities of financial innovations have led to a significant turmoil for society, more empirical works are needed to establish their effective role (positive or negative) with respect to the sustainability transition. Though, considering the extant institutional framework, such kind of endeavour is demanded for future developments of this work.

[30] Regulation 2017/2402 (EU)

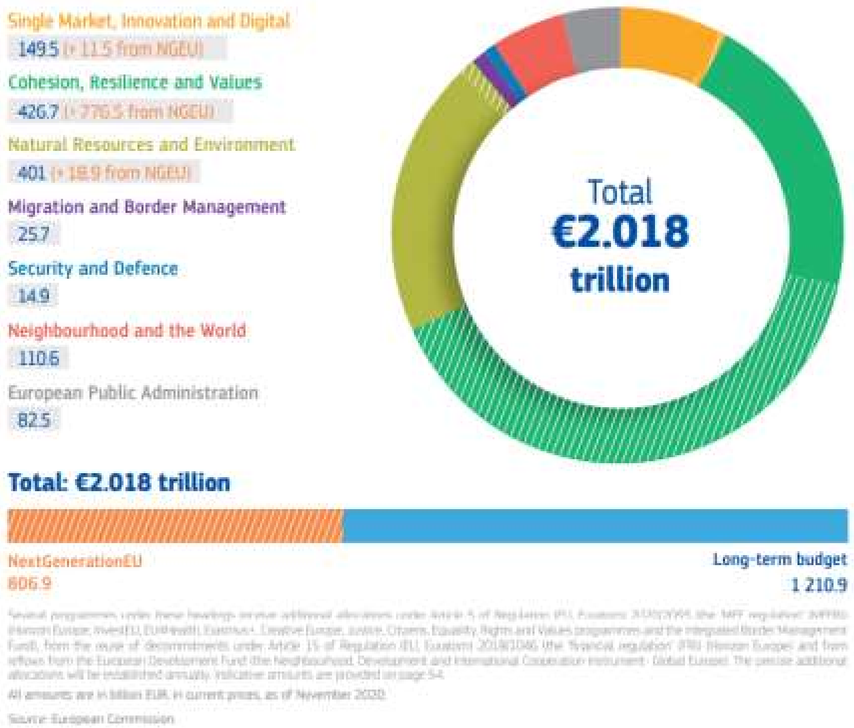
Conclusions

Market failures identify situations when the marketplace fails to allocate (efficiently) goods and services between demand and supply. Environmental pollution singles out a specific instance of failure related to externalities. An externality occurs whenever costs (or benefits) of a transaction affect a third party entirely external to the deal. The one underlined in this work is related to the consumption of the environment by humanity that is not paying its full price. In particular, human-made carbon dioxide emissions lead to abrupt changes in climate if not under control. Aside from agreeing on the necessity to set a price on the externality, the monetization of the environment is something quite difficult to undertake. Pricing the pressure of human activities enhancing environmental degradation entails economic and non-economic values. Indeed, one specific approach at the policy level envisions the role of the marketplace to provide the ideal price to the externalities. In other terms, letting the marketplace solve the market failure. However trivial this statement might seem, it hides a quite big challenge. As the first point, allocation should also be equal, aside from efficiency. Most regions of the world more responsible for climate change are not those more exposed to it. On a much smaller scale, a concrete solution might be that revenues from pricing pollution should be re-distributed among society. In policy terms, this approach might relieve some areas heavily burdened by public taxes (e.g., environmental tax shifting). Moreover, policymakers should be committed with respect to the approach they are undertaking to price externalities. For instance, in the context of carbon dioxide emissions, the choice falls between a carbon tax and the implementation of carbon markets. In both cases, political commitment shows a clear sign to society shaping production, consumption, and investment decisions. Considering its pivotal role, finance is a relevant aspect to consider when it comes to the sustainability transition. Financial markets provide efficient allocation of funds from supply to demand. This allocation is oriented considering the information financial actors collect about the risks of investments. However, if the climate-related risk has been identified, assessment mechanisms of these classes of risk are still a work in progress.

The three chapters of this work target specific issues related to possible flaws undermining the pathways to sustainability. Chapter 1 investigates the state of play of the EU carbon market and carbon price behaviour in influencing a broad set of dimensions. Chapter 2 identifies homogeneous groups among EU countries in light of the pathway towards sustainability. Chapter 3 provides insights on the role of financial innovations in tackling specific classes of risk related to sustainability-oriented investments. In this framework, the EU has been selected as the primary subject of analysis, considering its role as a leader in the transition towards sustainability. However, it is worth mentioning that no one-size fits all in the (environmental) policy application. The EU case represents sort of a singularity in the global landscape considering the ultimate aim it was founded. With the EU Green Deal, the Union has committed to reaching net-zero emissions by 2050 with progressively stringent objectives for all the areas of the sustainability transition. Besides, through its long-term budget, the European Commission has conceived an unprecedented stimulus package of € 2.018 trillion over 2021-2027 (European Commission. Directorate-General for the Budget, 2021). Part of those funds will be channelled through the so-called Next Generation EU with a total of € 806.9 billion as an immediate[31] relief in the aftermath of the COVID-19 economic crisis. This sum will be granted if the Member States comply with certain objectives considering all the pillars of sustainability (i.e., environmental, economic, social). This budget allocation has been designed to support the modernization of the EU with specific attention «to a fair climate and digital transition» with 30% of the budget earmarked to fight climate change, biodiversity protection, and address gender-related issues. Figure 16 summarises the overall amount of funds of the EU long-term budget disentangled in the different areas of allocation.

[31] According to the budget of the Next Generation EU, a total € 338 billion will be provided through grants whereas €385.5 billion will be provided through loans targeted to Member States under favourable conditions.

Figure 16 Summary of funds of the EU long-term budget 2021-2027



Source European Commission. Directorate-General for the Budget (2021)

As already mentioned in Chapter 1 and stated in European Commission. Directorate-General for the Budget (2021), revenues to fund this gigantic financial effort will also be gathered from the EU ETS and recent proposals (e.g., carbon border adjustment mechanism). Indeed, Chapter 2 disentangles how the process of harmonization in terms of policy implementation and outcomes might be something achievable. Still, the EU presents structural differences that can only be overcome with time. In this sense, as already mentioned in the Introduction, actions today exert significant repercussions in the future when it comes to sustainability. On the other hand, the EU sustainability transition also means more independence, for instance, in energy supply. As argued in Chapter 2, many Member States have been transitioning towards more sustainable energy sources also in light of cutting imports. In fact, Chapter 3 identifies how investments in renewable sources need extensive upfront costs with progressive returns once the plant becomes fully operational. Indeed, setting a reliable carbon price might further orient investment and consumption choices. From the last account, EUA prices set a record of € 89.27 €/tonne of CO_2 in December 2021[32] with concrete possibility of reaching €100. Aside from the recent adjustments made by the European Commission (e.g., Market Stability Reserve) those figures signal a perceived commitment by participants with respect to the policy. Still, considering all the limitations of the analysis Chapter 1 highlights how carbon prices exert a relative weak direct influence. On the other hand, the analysis did not take into account the recent increasing trends in EUA prices and other major events (e.g., Brexit, COVID-19 pandemics). Another significant issue emerged in the three chapters is related to harmonization of objectives among different areas of policy intervention. Mostly in Chapter 3, to undertake a cohesive transition of the financial sector, the framework at policy level should be consistently aligned with other interested areas (e.g., climate, environment, energy, biodiversity). Moreover, one specific source of risk for financial investors arises from the uncertainty of timing and depth of the transition of the overall policy landscape (e.g., transition risk). This issue is similar to what happened

[32] https://www.euractiv.com/section/emissions-trading-scheme/news/eu-carbon-price-could-hit-e100-by-year-end-after-record-run-analysts/

during the first Phases of the EU ETS when participants did not perceive a concrete political commitment by the EC on this policy. As a results, prices would frequently hit €0 per tonne of CO_2 and no transaction would take place. Thus, markets need a reliable background to function properly along with transparency on what might be the next steps policy-wise. In this sense, definitions are of the outmost importance for investors as to single out (non-)sustainable activities.

Thus far, this work highlighted the fact that both markets need to function properly to undertake a full transition towards sustainability. On the one side, well-functioning carbon markets might deliver a reliable price to emissions solving the market failure. Well-functioning financial markets provide an efficient allocation of financial resources towards more sustainable production and consumption patterns. Common traits of functioning markets are transparency, effective monitoring and enforcement mechanism, commitment. The case of the EU ETS highlighted some of those flaws during the early Phases of its implementation. Indeed, results in Chapter 1 highlighted how carbon markets (at least in the EU context) are still not quite interwoven with the overall human-environment system. On the other hand, the lack of the abovementioned features led financial markets to trigger one of the major economic downturns of this century. Imperfect information (or lack thereof) represents another cause leading to market failure. In fact, structural issues related to climate change studies have already been disentangled in the Introduction. Economics is that science dealing with allocation of scarce resources in constant lack of information. Transition towards sustainability will always deal with such kind of issues. However, the analysis in Chapter 2 pointed out cases of countries that are progressively shaping their consumption and production to cope with this structural scarcity. As a matter of fact, most of the resources that are now at the basis of the current production and consumption patterns (e.g., minerals, fossil-fuels) are not equally distributed among countries in the world. In this case, a more sustainability-oriented society might benefit from other more present resources. Countries with favourable climate (e.g., wind, sun) can maximize the benefits of those conditions making use of more renewable generation capacity. For instance, this was the case of Latvia and Estonia in the EU as elaborated in Chapter 2. Furthermore, Chapter 3 highlighted how it is possible to tackle some specific classes of risk related to renewable investments with tailored instruments. In this perspective, sustainability might be a new opportunity of thriving much more in line with the relative scarcity of resources a country may suffer.

Despite the contribution and the conclusions that might be drawn from the three works, some caveats are needed. First of all, when dealing with environmental issues one only reaches a partial analysis of the issue. The Planet is formed by different ecosystems in constant exchange of organic and inorganic matter among each other. Whether dealing with a specific ecosystem or the entire Planet this exchange contributes to reach an equilibrium (e.g., homeostasis). However, that is never permanent and multiple factors can perturbate this static condition possibly leading to another equilibrium. Human activities are a factor influencing the current equilibrium and scientists fear the new one would be not sustainable for the future prosperity of humanity (IPCC 2018b, 2019). By only looking at carbon dioxide emissions as source of environmental pressure this work makes an extreme simplification, yet necessary. However, as already mentioned in the Introduction it is worth stressing that changes in concentration of CO_2 in the atmosphere generate multiple repercussions in the whole biosphere. Indeed, this includes the human and more specifically the socioeconomic system. Thus, when trying to capture this complexity modelling makes a justifiable assumption of simplification. Mostly data employed for the analysis provide but a partial representation of the reality in some cases even a proxy.

Another set of limitations is more related to the specific instruments of analysis. Overall, the analytical strategy in this work has been conceived to try to encompass the complexity of the human-environment relationship. In fact, the choices of the statistical techniques in the chapters face the trade-off between accuracy and interpretability. Those models benefit of extensive flexibility and are suited to deal with many covariates of different nature. However, if not fine-tuned, the algorithms might not deliver clear-cut interpretable results James et al. (2013). Elementwise HVAR allows for extensive flexibility in the choice of the lags of the single series. On the other hand, cluster analysis is a totally data-drive approach without imposing any pre-existing hypothesis on the relationship among data. Structural limitations in Chapter 3 are mostly related to this still uncertain framework about definitions. Furthermore, the EU Taxonomy is mostly focused only on sustainable activities lacking the other significant side of non-sustainable one. Therefore, this overall work should be read as a snapshot of an extremely dynamic situation. Further development of the analyses in the chapters necessarily involve more updated data and information. As already disentangled the analysis in Chapter 1 did not cover Brexit and COVID-19 pandemics, two events with significant future impact on EU ETS. Chapter 2 acknowledges the discourse around the inclusion of nuclear power among sustainable activities within the EU Taxonomy. Whether considering this source as “transitional” or as a concrete sustainable alternative to fossil-fuels might shape a completely different pathway for the energy transition. In Chapter 3 definitions represent the elephant in the room of the discussion. In fact, the EU Taxonomy represents a concrete effort in a global landscape where definitions are still missing. At the time of writing, the latest news on the Taxonomy date back to July 2021 with the overall issue of nuclear power. Though, limitations are no more than future areas of investigation in the matter. In fact, this work should be also read in light of the potentialities that might stem out of it. Chapter 2 outlines a new potential use of a well-established analytical framework complementary to causal inference. Chapter 3 tries to contribute on framing the discussion to some quite relevant topics looking at financial innovation in a new light. Despite all the technical simplification made with respect to the time series econometrics framework Chapter 1 tries to deliver a comprehensive overview of the economy-environment system in the context of emission trading.

Overall, this work tried to contribute to the long-debated question as to what extent markets might be the ideal place to favour an efficient allocation of resources tackling externalities. Even in the case of this work, as in all economic science, the answer is: it depends. In fact, there are multiple factors involved in reaching this aim. Moreover, the issue around equality in allocation of resources is hereby cited but goes beyond the scope of the thesis. Still, equality represents the other relevant side of the sustainability transition given climate change will not impact humanity homogeneously. On the other hand, what emerged is that, whether financial or environmental, markets need a favourable context to perform efficient allocation. Furthermore, markets embed opportunities. One of the very structural hurdles to sustainable finance is the lack of a concrete incentive to invest in sustainability-oriented assets (e.g., *greenium*). On the other hand, certain classes of financial assets will be progressively losing value as an effect of climate change (e.g., stranded assets). As briefly argued in Chapter 1 carbon markets directly stem out of the Kyoto Protocol. Normally, those markets are mandatory as they are set by governments to cope with their international pledges. However, there are also instances of voluntary carbon markets and certificates that are mostly traded for offsetting purposes. In the EU ETS the cap is progressively decreasing over time according to a linear factor. Thus, supply in this particular market is destined to be scarcer as time goes by. The incentive for enterprises in this market would be to adopt lower-carbon technologies in order to decrease costs of production and in turn dependency from the market. Another significant hurdle for efficient market functioning is related to the definition of the object of transactions. This is more valid when it comes to sustainable finance with the overall discussion around sustainable and unsustainable activities (see Chapter 3). Overall, despite limitations findings in Chapter 2 highlight how the progressive attention to sustainability and low-carbon transition is shaping production and consumption decisions. If a transition is taking place, another significant part of the issue is related to the overall pace of this process. Transitions might take also a century to complete and as for a functioning marketplace they require transparency, commitment and a scope.

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