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01/2023

SEEDS Working Paper 01/2023
February 2023
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Note for the reader: this paper was originally presented during the Italian Society of Transport and Logistics Economists (SIET) XXIV Scientific Meeting, "Transport, Tourism and Sustainable Development" at the University of Insubria, Varese, on September 8th and September 9th 2022.

This paper refers to the existing legislation regarding "new rules on applying the EU emissions trading system in the aviation sector" which was being drafted at the moment of writing. The legislation can be accessed here: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7609.

Abstract

Aviation is generally recognized as one of the most carbon intensive forms of transport. The sector accounts for roughly 2.5% of global CO2 emissions (which would place it as a top-10 emitter if ranked as a country), but this absolute value is of less concern than its accelerated and continuous growth in the last decades. In order to tackle aviation's environmental impact, in 2012 the sector has been (partially) included in the European Union Emission Trading System (EU ETS), a market-based mitigation mechanism designed to put a price on carbon emissions and create an economic incentive towards their reduction. In the recently announced Fit for 55 legislative package, proposed by the European Commission in order to reach its medium-term environmental objective (a 55% reduction of greenhouse gases emissions by 2030 compared to 1990 levels), a revision of the system is envisaged, reinforcing the rules concerning aviation and making emission mitigation through the system more and more costly in the upcoming years. In light of this, the need for a predictive model to forecast the carbon price is of main importance.

Several studies in the literature faced the problem of finding a reliable predictive model for the carbon price, but no one seems to completely satisfy the scientific community, mainly for the complexity of the algorithms and their poor predictive reliability. In this work, after an introductory section exploring the history and the characteristics of aviation's inclusion in the EU ETS, a literature review of the studies investigating the topic has been carried out. Then, a simple data-driven methodology has been developed by using the dynamic mode decomposition (DMD) algorithm. For this purpose, a freely available set of data containing the daily carbon price since 2015 has been used. The main advantage of this approach is its

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simplicity and its ability to catch the non-linear dynamics of the phenomena. The presented strategy could inform policy makers at European level and help the industrial and financial sectors in the prediction of the carbon price by using a simple methodology.

1. Introduction

Mitigating the environmental impacts of civil aviation is undeniably one of the most difficult challenges for sustainable transportation researchers. The sector accounts for roughly 2.5% of global CO2 emissions plus non-CO2 effects, which may amount to 2/3 of the total net radiative forcing (Lee et al., 2021). The reasons behind the complexity of this issue are many: the difficulties related to restraining aviation activity due to its importance in connecting nations in a globalized world; technical barriers, industry structure, and its lobbying capacity (Efthymiou and Papatheodorou, 2019); the fact that the connection between aviation and climate change has been de facto ignored by media and institutions for a long time (Gössling, 2020); the issue of replacing kerosene with SAFs (Sustainable Alternative Fuels) which is an extremely challenging process, as some of these alternative fuels may actually generate worse impacts than traditional fossil fuels (O'Connell et al., 2019, Pavlenko & Searle, 2021) whereas other sustainable alternatives have production costs that are up to ten times higher than traditional jet A-1 kerosene and require substantial policy measures to stimulate market uptake and bring down production costs (Zhou et al., 2022).

In order to tackle aviation's CO2 emissions, the European Union adopted in July 2008 Directive 2008/101/EC that included the aviation sector under the umbrella of the European Union Emission Trading System (EU ETS). The EU ETS is a transboundary cap and trade scheme established in 2005 designed to fight climate change in a way that is both economically efficient and legally rigorous (Borghesi et al., 2016). The system entitles the EU Commission to set a yearly EU-wide cap of emission allowances that correspond to equivalents of CO2 metric tons. Allowances are allocated within the EU and the economic actors subject to the scheme's application have to monitor and report their greenhouse gasses (GHG) annual emissions in order to surrender every year a number of allowances equal to their emissions produced in the previous year. These economic actors may comply with this obligation by improving their environmental performance (i.e. cutting their GHG emissions) or by buying the allowances on the related auctioning and trading market. Currently, two types of emission allowances are used, EUAs (European Union Allowances), and EUAA (European Union Aviation Allowances). Until 2020, aviation was allowed to submit both types of allowances to comply with the regulations, whereas stationary sources were bound to EUAs.

Aviation was effectively incorporated in the EU ETS on the 1st of January 2012 and required all airlines departing or arriving at an EU airport to surrender allowances covering the emissions of all EU flights they had operated in a given year. Until at least 2020, all flights from or to European airports were envisaged to be included in the scheme, apart from a few exemptions. However, following an international outcry and in order to ease ongoing negotiations at the International Civil Aviation Organization (ICAO) where carriers were negotiating a global mitigation mechanism, the European Union decided to limit the coverage of the EU ETS to emissions from internal flights within the European Economic Area (EEA) (i.e. flights departing and arriving at an airport in the EEA) for the period from 2013 to 2016 (the so-called "stop-the-clock" decision - Decision no. 377/2013/EU). When minimal progress was made at ICAO's 38th assembly in October 2013, the clock was stopped again. In 2016, ICAO managed to agree on a global measure, CORSIA (the Carbon Offsetting and Reduction Scheme for International Aviation), and the Commission proposed to extend the exemption indefinitely, pending a review of the effectiveness of the scheme. The co-legislative process eventually settled on an extension until 2024, when further details about CORSIA and its alleged efficacy will be known. CORSIA's structure and functioning will not be discussed in this paper; for our purpose, it is sufficient to note that there are serious questions about the scheme's effectiveness in terms of emission reduction (Gössling and Humpe, 2020; Scheelhaase et al., 2018; Larsson et al., 2019).

The capability of the EU ETS to reduce CO2 emissions depends greatly on the number of allowances issued every year. For the aviation sector, from 2013 until 2020, the total quantity of allowances allocated to aircraft operators is limited to 95 percent of the average historical aviation emissions of the years 2004–2006 (so-called overall "cap"). Aircraft operators have the option to use up to 15% of the auctioned allowances from the greater pool of EUAs; from those traded by other aircraft operators (European Union Aviation Allowances, EUAAs); and from other eligible international projects (limited to a maximum of 1.5% of the annual verified emissions). Regarding the allocation method, the Directive states that 82% of allowances are allocated for free to aircraft operators while 15% is allocated through the auctioning system (the remaining 3% go to a special reserve for later distribution to new entrants and fast-growing airlines). The actual allocation of allowances is scaled down from 2013 to 2023, to take account of the temporary reduction of the scope of the EU ETS to flights between airports in the European Economic Area ("stop-the-clock"). The fact that the majority of allowances are freely allocated to the aviation sector is one of the main reasons for the so far negligible economic and environmental impacts of the scheme that will be highlighted in the subsequent literature review.

The second fundamental variable for the effectiveness of the scheme is the price level of the allowances. This price is determined at primary auctions based on relative demand and supply. After an initial period of low prices (around 5€ from 2012 to 2017) allowance prices have constantly increased. This rising trend is the result of several policy measures introduced to stabilize allowance prices and create greater market tightness, such as delaying auctions (the so-called "back-loading"), and introducing mechanisms designed to avoid a surplus of allowances and improve the system's resilience to shocks (market stability reserve). Moreover, since 2020, prices have risen exponentially mainly because of the introduction of increasingly stringent climate change policies in the EU and globally alongside various changes in ETS market design. As of July 2022, the price of an EU ETS allowance has risen to around 85€. Nevertheless, in order to bring the sector in line with the goals of the Paris Agreement much more action by regulators is required, inside and outside of the EU ETS.

In July 2021, the European Commission presented a legislative package designed to meet its medium-term environmental objectives (a 55% reduction of GHG emissions by 2030 compared to 1990 levels) known as "Fit for 55". Aviation is directly involved in three of these legislative proposals: the revision of the Energy Taxation Directive with the introduction of a jet fuel tax for intra-EU flights; the ReFuelEU Aviation initiative, introducing a blending mandate for SAFs; and the revision of the EU ETS for aviation. For reasons of space and clarity, this paper will focus only on the third legislative proposal.

The European Commission proposed a strengthened EU ETS for aviation, with a progressive phase-out of the free allowances allocated to aircraft operators from 2024 to

2026 by respectively 25%, 50%, and 75%, and a complete phase-out from 2027 onwards (with full auctioning); in addition, the annual linear reduction factor of EUAAs will be almost doubled, moving from 2.2% to 4.4%. Regarding the coexistence of the scheme with CORSIA, the EU ETS would continue to apply to intra-EEA flights as well as flights to the UK and Switzerland, exempting those flights from CORSIA. For other international flights, EU airlines would be obliged to apply ICAO's scheme. On the 8th of June 2022, the European Parliament adopted an even stronger position on the matter, proposing a full phase-out of free allowances as early as 2025 and a return to a "full-scope" ETS (covering all flights departing from EU airports regardless of their destination). The European Parliament, Council, and Commission will now enter "trilogue" negotiations hoping to conclude the political process by the end of 2022.

Given all this, the importance of the EU ETS for aviation and, more specifically, the level of the carbon price is thus becoming more and more significant for the sector, both from an economic and an environmental point of view. Moving from this assumption, in the second section of this paper, a selected literature review composed of studies analyzing this peculiar subject will be developed. It will be divided into two streams, from early literature to the latest studies. Subsequently, in the third section, a brief literature review on carbon price forecasting will be presented. In the fourth section, a simple data-driven methodology for the prediction of the carbon price will be carried out, using the Hankel alternative view of Koopman (HAVOK) algorithm. Finally, in the fifth section results and conclusions will be presented, together with some considerations on the next possible steps for this study and this line of research.

2. Literature review on the EU ETS and aviation

Given the aforementioned motivations, our selected literature review will be focused on studies investigating specifically aviation and the EU ETS. The review will be divided into two streams. The first one is composed of a number of early studies investigating the possible impacts of the inclusion of the aviation sector in the EU ETS from different points of view, mainly its economic and environmental impacts inside and outside the European Union and its potential for induced airline network reconfiguration. The motivations, specifications, and model designs behind all these studies stem from the July 2008 European Union's directive on the inclusion of aviation in the EU ETS (Directive 2008/101/EC) and they are all antecedent to the "stop-the-clock" decision (Decision no. 377/2013/EU) which, as explained in the introduction, completely changed the scope of aviation's inclusion in the trading scheme. For these reasons, we decided to group these studies together. In fact, even if the final assessments of these studies have been surpassed by the consequent policy developments, they remain meaningful as they contributed greatly to the creation of a modeling framework for future studies. Moreover, it is interesting to analyze the findings of these studies in a counter-factual perspective in order to understand what could have been the impacts of the original directive if the "stop-the-clock" decision would have not been taken.

The second stream of literature is composed of studies which were published after the "stop-the-clock" decision. These studies built on the foundation of the previous stream and revised the model assumptions in accordance with the new policy environment. Moreover, after 2016, some of the revised studies investigated the links and policy implications between the EU ETS and ICAO's global carbon mitigation scheme, CORSIA. Finally, the most recent study included in our literature review was published after the proposed July 2021 revision of the scheme in the context of the "fit-for-55" legislative package. The analysis of this study and its policy recommendations will conclude our literature review.

2.1 First stream (2009-2013)

As was already noted, the foundation of these studies is mainly the July 2008 directive on the inclusion of the aviation sector in the EU ETS. The first study under our scrutiny is a meta-study by Anger and Kölher (2010). The decision to start our review in 2009 was not in fact taken because no studies on the subject existed before this date. On the contrary, Anger and Köhler (2010) analyze nine different studies published between 2005 and 2009, as the political discussion around the inclusion of aviation under the umbrella of the EU ETS was going on for several years before the July 2008 Directive. There are three main reasons why these studies are not included in our literature review which are made explicit by the meta-study itself. First of all, the majority of these studies belong to the grey literature, which are consultancy reports that are not peer-reviewed. Secondly, some of these studies are based on assumptions that differ from the final legislation, regarding for example the auctioning rate of allowances. Finally, the authors note an over-simplification of the models and calculations used in these studies, often accompanied by the omission of important variables. In any case, all the reviewed studies forecast limited effects of aviation's inclusion in the scheme, both from an environmental and economic viewpoint: CO2 emissions are projected to decline by a maximum of 3.8% and GDP to decline by a maximum of -0,0002% by 2020.

Following the criticism highlighted above, Anger (2010) develops her own model to investigate the impacts of the EU ETS on air transport. Using a hybrid post-Keynesian macroeconomic dynamic simulation model, the author develops three allowance price scenarios and compares them with a reference scenario, forecasting impacts on industry activity and carbon emissions. In terms of demand reduction, a slight decrease in demand is projected by 2020 (0.04% for an allowance price of €5, 0.54% for an allowance price of €20, and 0.98% for an allowance price of €40, compared with the reference scenario); regarding carbon emissions by the industry, the study forecasts a decrease of respectively 0.3%, 3.4% and 7.4% in the three scenarios. Finally, changes in real GDP in the EU are found to be either nonexistent or very small (0.02% in the high price scenario). It is worth noting that while demand reduction effects are found to be smaller than in the previous literature, CO2 emission reductions are greater than previously estimated.

Another study investigating these effects is Vespermann and Wald (2011). These authors build a simulation model in order to investigate the impacts of the scheme on the sector until 2020. Regarding the economic effects, they foresee the industry burden to rise from € 2.25 billion after the introduction of the ETS system to about € 3.67 billion in 2020, which translates into a cost base increase of about 1.25%. Regarding the demand side, passenger growth in 2013 is estimated to be reduced by 0.7% compared to the unrestricted base scenario, and this reduction is expected to rise to about 6% by 2020. However, the authors note that these impacts are highly dependent on external settings, such as allowance prices and demand growth. Regarding the emission reduction effects, the model shows that even if in the first years after the introduction of the ETS scheme emissions reductions will be comparably low (<3%) the system will unfold its impact in the mid- and long-term, generating a CO2 emission reduction of 7.7% in 2020. The authors also make an observation on possible competition distortion arising from the scheme but find those impacts to be rather low.

The impact on competition between European and non-European network airlines is the subject of another study analyzed in this section carried out by Scheelhaase et al. (2010). Their model-based analysis focuses on the competitive impacts of the EU ETS on EU- and US-based network carriers, drawing a comparison between two exemplary airlines, namely Lufthansa and Continental Airlines. In contrast with Vespermann and Wald (2011), their model shows how under the carbon mitigation scheme Continental would gain a significant competitive advantage compared to Lufthansa on the market for long-haul air services. This result could in turn be extended to all European network carriers competing with non-EU network carriers on markets for long-haul air services. Their opinion is that the EU should address this systematic problem by introducing separate benchmarks for different types of routes, separating at least long-haul from short-haul flights to avoid or at least reduce this competitive distortion.

Malina et al. (2012) also indirectly investigate competition effects by estimating the economic impacts of the directive on US airlines from 2012 to 2020. These authors link an economy-wide computable general equilibrium model with a partial equilibrium model focused on the aviation industry. Their results are quite striking, in the fact that not only they forecast a relatively small impact on aggregate traffic and carbon emissions (3% CO2 emission reduction compared to the reference scenario) but in their full cost pass-through scenario the model shows a potential for windfall gains amounting to $2.6 billion associated with the opportunity cost pass-through that arises from the grandfathering allocation procedure (i.e. free allocation) of the emission allowances.

The last two studies reviewed in this section are Albers et al. (2009) and Derigs and Illing (2013). Both studies estimate possible airline network reconfigurations following the adoption of the Directive. The first study models potential policy-induced cost increases for individual passenger routes and concludes that the magnitude of the induced effects is too small (between €9 and €27 per route) to instigate major route reconfigurations among European airlines. Derigs and Illing (2013) focus on the air cargo network and come to the same conclusion, stating that the EU ETS rules planned for the first years will result in insignificant or only marginal impacts on emissions and cost increases as well. It is worth noting their conclusion on the whole matter: "Only aggressive rules by which cost per allowance is raised significantly and free allowances are skipped lead to the intended reduction of CO2 emissions".

2.2 Second stream (2016-2022)

As was mentioned in the introductory section, in 2013 two impactful events occurred in the context of aviation, sustainability and mitigation market-based measures. At the European level, with the "stop-the-clock" decision, the scope of the EU ETS for aviation was restricted to only intra-EEA flights. At the global level, the 2013 ICAO Assembly agreed on the development of a global market-based scheme designed to mitigate aviation's carbon emissions. The proposed scheme would later become known as CORSIA (Carbon Offsetting and Mitigation Scheme for Aviation) and would be officially adopted in the 39th ICAO Assembly in October 2016. These two decisions inevitably affected the subsequent literature on the subject: in this section, we will first review two studies analyzing the economic effects of the EU ETS on Italian airlines before moving on to a number of papers investigating the new regulatory environment and the coexistence perspectives of the two mitigation schemes.

Meleo et al. (2016) add their contribution to the previously analyzed line of research of cost evaluation as they focus on Italian airlines. These authors develop a cost calculation for the period 2012-2014 plus a forecast of future costs for the years 2015-2016, referring to three scenarios related to different hypotheses on allowance price (low, medium, and high scenarios). Their results show that direct costs linked to the scheme are quite limited but are expected to slightly increase from 2016 in reaction to the reduction of surplus allowances and rising carbon prices. Expanding the analysis from this model, Nava et al. (2018) find that two main factors influence airline profits when the EU ETS is enforced: the share of freely granted allowances and the airlines abatement effort cost, with a higher share of free allowances being associated to lower incentives for airlines to reduce emissions.

A different but still meaningful approach to this subject comes from Efthymiou and Papatheodorou (2019). These authors examine policy issues related to the implementation of the EU ETS in the aviation sector through a two-round Delphi study based on a sample of 31 expert stakeholders. The answers given to the questionnaire confirm the relevance of three main elements affecting the efficiency and the design of the mitigation scheme: the allocation of emission allowances, the policy influences on the market, and the linking of the EU ETS with other schemes. It is worth noting that even if stakeholders working for airlines or IATA (International Air Transport Association) expressed similar views on the relaxation of environmental regulations whereas academics and government representatives pushed for stricter allocation methods, all stakeholders agreed on the fact that lobbying influences the EU ETS and more generally environmental policy design as a whole. As the authors clearly state, "in the area of EU ETS in aviation, the most influential players are the airlines and the governmental institutions with conflicting interests regarding environment."

Moving to the analysis of the studies comparing CORSIA and the EU ETS, Scheelhaase et al. (2018) weigh up the two aforementioned mitigation schemes in terms of functioning and future perspectives, focusing on their differences (CORSIA is an offsetting scheme, while the EU ETS is a cap-and-trade scheme) and outlining political options for the EU to adjust its own scheme in light of CORSIA's introduction. The authors list several coexistence policy options and conclude by stating that a continuance of the EU "reduced scope" regime beyond 2020 and a parallel coverage of international flights by CORSIA would be the best option as a compromise between political feasibility and environmental effectiveness. It is worth noting that as was reported in the introduction this option was in fact the one proposed by the EU Commission in the context of the reform of the EU ETS for the aviation sector included in the "fit-for-55" legislative package (the European Parliament, however, proposed a return to a "full-scope" EU ETS).

A similar conclusion is reached by Maertens et al. (2019) in a study that focuses on the options to continue for the EU ETS in a CORSIA-world. The authors stress again the difficulties in directly comparing the two mitigation schemes, given their structural differences, and pose questions on the environmental effectiveness of CORSIA's CERs (Certified Emission Reductions). The analysis carried out concludes by stating that keeping the intra-European EU ETS in addition to the introduction of CORSIA on other international routes would have far greater mitigation effects than CORSIA alone, even if this would likely create political tensions between ICAO and the European Union.

Another study worth mentioning is Larsson et al. (2019). This paper analyzes both national and international emissions mitigation policies for aviation and forecasts the effects of the EU ETS and CORSIA on the expected development of air travel emissions from 2017 to 2030 for the sample country Sweden, finding these impacts to be far too limited to achieve the 2°C target contained in the Paris Agreement. Alternatively, these authors cite three legally feasible national policy options which could, in their opinion, greatly help in the undertaking of limiting aviation's carbon emissions. These are the introduction of a tax for jet fuel, a distance-based air passenger tax, and a quota obligation for biofuels.

The last study reviewed in this section is a very recent paper by Scheelhaase et al. (2022) that followed the Commission proposal to reform the EU ETS for aviation in the "fit-for-55" package. Here, the authors extensively discuss possible options for coexistence between the two schemes in light of the July 2021 legislative proposal. They highlight a number of key challenges to be addressed in the final legislation, including the geographical scope of the EU ETS for aviation, the level of auctioning of the allowances, and the level of the CO2 emission cap. They also present some selected quantitative results illustrating potential effects on airfares of the proposed revision, under a full auctioning assumption (which is currently envisaged to be enforced by 2025 or 2027 according to the proposed reform) and a full cost pass-through to passengers. Their calculations result in a 2.6%, 5.9%, and 9% airfare increase for an allowance cost of respectively €45, €83, and €120. The authors conclude their study with a recommendation for policy makers to tackle some critical issues, such as the linkage between the two schemes, the need to strengthen CORSIA offsetting effectiveness, and to deal with potential carbon leakage and competitive distortion.

3. Literature review on carbon price forecasting

The preceding literature review has showed how the level of the carbon price is one of the fundamental variables in the investigation of the climate and economic impacts of all ETS-related activities and policies. In fact, many of the scrutinized studies adopted a scenario strategy where different carbon price levels were hypothesized in order to estimate projected costs and impacts. This approach is a consequence of the intrinsic uncertainty of the carbon price in the EU ETS which is, as we have seen in the introduction, dependant on several interrelated factors such as demand and supply dynamics, policy measures, international cooperation, and financial markets. However, a different approach to this uncertainty issue exists and it is embodied by studies developing carbon price forecasting models. In the next sections these techniques will be briefly mentioned and an original model will be presented, followed by some conclusions on the model's results and its applicability to our object of study.

As was already mentioned before, the inherent nonlinearity of the carbon price in EU ETS is the most challenging issue that has to be faced to accurately predict its behaviour over time. Several studies tried to tackle this problem by using univariate or multivariate linear models, including ARIMA, Factor-Augmented VAR, VARMA, and MIDAS (Chevallier, 2010; Koop & Tole, 2012; García-Martos et al., 2013; Guðbrandsdóttir and Haraldsson, 2011; Zhao et al., 2018). Despite the good results, the volatility of the carbon price in EU ETS does not allow to reach accurate results from these techniques. In this regard, with the increase in computational resources, the use of machine learning techniques became more and more extensive in the price prediction community (Atsalakis, 2016; Zhu, 2016; Fan et al., 2015; Xu et al., 2020). In particular, their coupling with the linear models above mentioned showed marked improvement in the predictive capability (Huang et al., 2021). Nonetheless, these methodologies are complex and difficult to be implemented. For this reason, in this work, a simple data-driven technique is proposed for the prediction of the carbon price in EU ETS.

4. Data-driven carbon price prediction model

This section presents a different methodology to predict the carbon price over time. After a brief introduction of the Koopman theory, the modelisation strategy is discussed and assessed. The CO2 price dataset is directly used to feed the algorithm in order to evaluate its forecasting capability.

4.1 Koopman operator theory

Koopman spectral analysis was introduced in 1931 by B. O. Koopman (Koopman, 1931) to provide an operator-theoretic perspective on dynamical systems. The theory was then generalized in 1932 by Koopman and von Neumann to systems with continuous spectra (Koopman & Neumann, 1932).

Throughout the paper, we will consider continuous-time dynamical systems of the form:

$$\frac{d}{dt}\boldsymbol{x}(t) = \boldsymbol{f}(\boldsymbol{x}(t)) \tag{1}$$

where $\boldsymbol{x} \in \boldsymbol{M}$ is an *n*-dimensional state on a smooth manifold $\boldsymbol{M}$, and t is the time. We will also consider the induced discrete-time dynamical system:

$$\boldsymbol{x}_{k+1} = \boldsymbol{F}(\boldsymbol{x}_k) \tag{2}$$

where $\boldsymbol{x}_k = \boldsymbol{x}(kt)$ may be obtained by sampling the trajectory in Eq.(1).

The Koopman operator $\mathcal{K}$ is an infinite-dimensional linear operator that advances measurement functions g of the state $\boldsymbol{x}$ forward in time according to the dynamics in Eq.(2):

$$\mathcal{K}g \triangleq g \circ \boldsymbol{F} \quad \Rightarrow \quad \mathcal{K}g(\boldsymbol{x}_k) = g(\boldsymbol{x}_{k+1}) \tag{3}$$

Because this is true for all measurement functions g, $\mathcal{K}$ is infinite-dimensional and acts on the Hilbert space of state functions. For a more detailed discussion on the Koopman operator, the reader is referred to Brunton et al. (2016).

Consider a measurement subspace spanned by measurement functions $\{g_1, g_2, \dots, g_p\}$ so that for any measurement g in this subspace

$$g = \alpha_1 g_1 + \alpha_2 g_2 + \cdots + \alpha_p g_p \tag{4}$$

In this case, we may confine the Koopman operator to this p-dimensional measurement subspace and obtain a $p \times p$ matrix representation $\boldsymbol{K}$. If such matrix representation exists, it is possible to define a linear system that advances the measurement functions, restricted to the subspace in Eq.(4), as follows:

$$\boldsymbol{y}_{k+1} = \boldsymbol{K}\boldsymbol{y}_k \tag{5}$$

where $\boldsymbol{y}_k = \left[g_1(\boldsymbol{x}_k) \quad g_2(\boldsymbol{x}_k) \ \dots \ g_p(\boldsymbol{x}_k)\right]^T$ is a vector of measurements in the invariant subspace, evaluated at $\boldsymbol{x}_k$.

In practice, obtaining such a representation in terms of a Koopman invariant subspace is extremely challenging. Because of this, the perspective of a data-driven linear approximation to a dynamical system is still valuable. In the following, we will show the application of the data-driven method proposed by Brunton et al. (2017) to estimate the Koopman operator as best as possible, to forecast the CO2 price during time.

4.2 Hankel alternative view of Koopman (HAVOK) method

This section formulates the HAVOK method for univariate time series analysis. The algorithm consists of three stages: (1) Time delay embedding, (2) dynamic mode decomposition, and (3) reconstruction and forecasting. Each step is explained in more detail in the following subsections.

4.2.1 Time delay embedding

The HAVOK modelisation tries to reconstruct a dynamical system from a sequence of observations of the system's state.

The first step of the algorithm consists of the generation of a so-called Hankel matrix by rearranging the dataset. In particular, the time delay embedding strategy proposed by Takens is used (Takens, 1981).

The strategy can be thought of as a mapping that converts a univariate time series $\boldsymbol{x}_k = [x_1, x_2, \dots, x_T]$ into a multidimensional series $\boldsymbol{H} = \left[\overline{\boldsymbol{x}}_1, \overline{\boldsymbol{x}}_2, \dots, \overline{x}_p\right]^T$, where $\overline{\boldsymbol{x}}_n = [x_n, x_{n+1}, \dots, x_K]$. Thus, the time series is decomposed into $K = n + T - p$ overlapping segments of length p. The structure of the matrix $\boldsymbol{H}$ is the following:

$$\boldsymbol{H} = \begin{bmatrix} x_1 & x_2 & \dots & x_p \\ x_2 & x_3 & & x_{p+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_K & x_{K+1} & \cdots & x_{K+p-1} \end{bmatrix} \tag{6}$$

4.2.2 Dynamic Mode Decomposition (DMD)

The Dynamic Mode Decomposition (DMD) was firstly introduced by P. J. Schmid in 2008 (Schmid, 2008). Shortly after, the work of Rowley et al. (2009) showed a strong connection between the DMD and the Koopman spectral analysis. In particular, the DMD provides a practical framework to approximate the Koopman operator.

The DMD algorithm aims to find the best-fit linear model to relate the following two data matrices:

$$\boldsymbol{X} = \begin{bmatrix} | & | & & | \\ x_1 & x_2 & \dots & x_{m-1} \\ | & | & & | \end{bmatrix} \qquad \boldsymbol{X}' = \begin{bmatrix} | & | & & | \\ x_2 & x_3 & \dots & x_m \\ | & | & & | \end{bmatrix} \tag{7}$$

The matrix $\boldsymbol{X}$ contains snapshots of the system state in time, and $\boldsymbol{X}'$ is a matrix of the same snapshots advanced a single step forward in time. These matrices may be related by a best-fit linear operator $\boldsymbol{A}$ given by

$$\boldsymbol{X}' = \boldsymbol{A}\boldsymbol{X} \Rightarrow \boldsymbol{A} \approx \boldsymbol{X}'\boldsymbol{X}^* \tag{8}$$

where $\boldsymbol{X}^*$ is the pseudo-inverse, obtained via the singular value decomposition (SVD). In this way, we can obtain a linear operator $\boldsymbol{A}$ capable to advance a matrix $\boldsymbol{X}$ in time.

4.2.3 HAVOK

HAVOK analysis (Brunton et al., 2016) provides linear representations for the dynamics of the dynamical systems ($\boldsymbol{f}$ in Eq. (1) and $\boldsymbol{F}$ in Eq.(2)). The first step of the algorithm consists of the finding of the eigen-time-delay coordinates by taking the singular value decomposition (SVD) of the Henkel matrix:

$$\boldsymbol{H} = \begin{bmatrix} x_1 & x_2 & \dots & x_p \\ x_2 & x_3 & & x_{p+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_K & x_{K+1} & \cdots & x_{K+p-1} \end{bmatrix} = \boldsymbol{U\Sigma V}^T \tag{9}$$

The columns of $\boldsymbol{U}$ and $\boldsymbol{V}$ from the SVD are arranged hierarchically by their ability to model the columns and rows of $\boldsymbol{H}$, respectively. $\boldsymbol{H}$ can be well approximated by the first r columns of $\boldsymbol{U}$, $\boldsymbol{V}$. According to the HAVOK analysis (Brunton et al., 2016), the first $r-1$ variables in $\boldsymbol{V}$ can be built as a linear model:

$$\boldsymbol{v}(t+dt) = \boldsymbol{A}\boldsymbol{v}(t) \tag{10}$$

where $\boldsymbol{v} = [v_1 \ \ v_2 \ \ \dots \ \ v_{r-1}]^T$ is a vector of the first $r-1$ eigen-time-delay coordinates. The linear system in (10), specifically the matrix $\boldsymbol{A}$, was derived by applying the DMD.

4.3 Model assessment

After building the time-delay embedded data matrices, we have to find the value of the best-rank approximation (r) as introduced in the previous paragraph before applying the DMD algorithm. This is done by analysing the singular values of the matrix Σ coming from the application of the SVD to the main matrix. The results in terms of $\sigma_r = diag(\Sigma)/\mathrm{sum}(diag(\Sigma))$ and $\sigma_r = cumsum(diag(\Sigma))/\mathrm{sum}(diag(\Sigma))$, where $cumsum()$ is the function "cumulative sum", are shown in Figure 1. From Figure 1(b), it can be noted that to achieve the 90% of the total information, a rank equal to roughly 150 has to be chosen. Nonetheless, it can be noted from Figure 1(a) that for rank values above 140, the eigenvalues become so small to be considered negligible. In view of this, a rank of

140 has been chosen for the present study, leading to roughly the 87% of the total information.

To demonstrate the capability of HAVOK for CO2 price forecasting, data from 01-Jan-2005 to 11-Mar-2022 have been used as the training set, leaving the remaining data, from 11-Mar-2022 to 31-Mar-2022, as the test set. The results of the assessment are shown in Figure 2, where is reported the training data with the black line, the reconstructed trend with the yellow line, the test data with the blue line, and the predicted trend with the red line.

First of all, a good agreement between the training data and the reconstructed trend can be observed. This confirms that the rank value chosen is correct, hence the capability of describing the entire behaviour with a reduced order model.

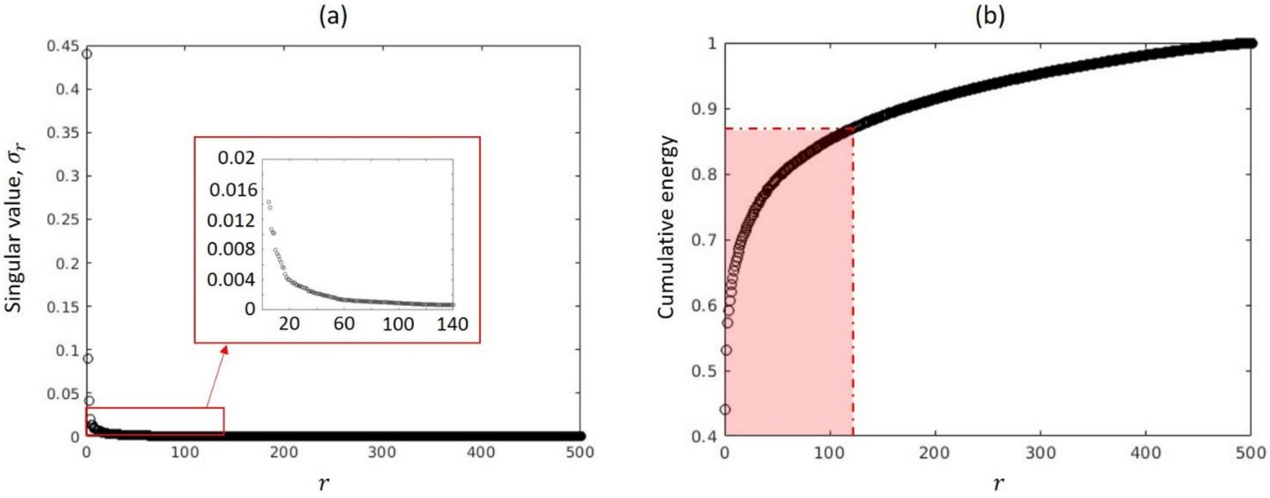

Figure 1 - Singular values σ_r *(a) and cumulative energy in the first* r *modes (b).*

What concerns the predictive capability assessment, can be adequately discussed by observing the zoom in Figure 2. In particular, it can be recognized that HAVOK can well capture the trend for the first 12 days, but began to be unstable beyond this value. Although the prediction is considered acceptable only for 12 days beyond the training data, the authors want to stress that this is the first attempt to find a data-decomposition predictive model for the EU ETS CO_2 forecasting.

Moreover, a daily resolution as the time discretization has been considered, hence the 12 days could be 12 months if the time resolution had been monthly. The latter consideration, that is the sensibility of the predictive algorithm to the time resolution, will be the focus of the next steps of the research. Concerning the instability behaviour, this is due to the fact that the eigenvalues of the linear operator are for the most part outside the unit circle on the Argand-Gauss plane. A possible cause of this problem may be the time resolution chosen for the present study (daily).

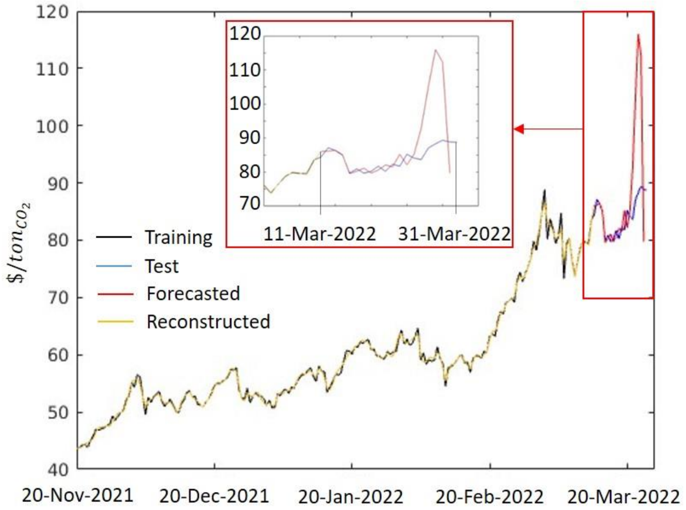

Figure 2 - CO_2 price forecasting assessment

5. Conclusions

The first part of this paper focused on the historically complex relation between the EU ETS and the aviation sector. After an introductory section explaining the basic functioning principles of the scheme and its developments with respect to the aviation sector in the last few years, our literature review demonstrated that the environmental and economic impacts of the EU ETS on the sector have been fairly negligible and highlighted the need for a systematic reform of the scheme, especially in the areas of allowances allocation methods and its relationship with ICAO's global offsetting scheme, CORSIA. As we have seen, the European Union has started the political process to carry out such reforms in the context of the "Fit for 55" package; at the time of writing this legislation is still being discussed between the EU's institutions and we expect to have a definitive framework by the end of the current year. When this final legislation will be agreed upon, researchers should have the elements to carry on research to investigate the impacts of the new EU ETS for aviation. However, a fundamental part of the equation will remain subject to an inevitable degree of uncertainty: the level of the carbon price.

For this reason, in the second part of this paper, a predictive model to forecast the carbon price has been developed. After a literature review of the existing predictive methodologies, a simple data-driven technique is proposed in order to face the implementation complexity of the already present methods. The proposed strategy called HAVOK has shown a good predictive capability for the carbon price in the EU ETS. Specifically, it captures the trend for the first 12 days but began to be unstable beyond this value.

In conclusion, the relationship between the EU ETS, the aviation sector, and the level of carbon price remains an intriguing and extremely significant line of research. Even if the reform of the scheme for the aviation sector is still being discussed, future research could forecast the impacts of the EU ETS on the aviation sector under different reform assumptions. Our predictive model could be integrated in a broader economic model in order to estimate future costs of the EU ETS on airlines based on the predicted carbon price. An even broader line of research could include those findings into a model taking into account also the impacts of other relevant legislation, such as the ReFuelEU Aviation initiative or the introduction of a jet fuel tax in the context of the upcoming reform of the Energy Taxation

Directive. Aviation remains one of the most carbon-intensive modes of transportation and its environmental impacts have to be mitigated in order to achieve the climate objectives of the European Union and of the Paris Agreement. Research has to support policies and companies operating in a sector that has been structurally and historically refractory to change in order to find ways to effectively reduce its environmental impacts while at the same time avoiding to deliver fatal blows to its economic profitability.

References

Albers, S., Bühne, J. A., & Peters, H. (2009). Will the EU-ETS instigate airline network reconfigurations? *Journal of Air Transport Management*, *15*(1), 1–6. https://doi.org/10.1016/j.jairtraman.2008.09.013

Anger, A. (2010). Including aviation in the European emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU. *Journal of Air Transport Management*, *16*(2), 100–105. https://doi.org/10.1016/j.jairtraman.2009.10.009

Anger, A., & Köhler, J. (2010). Including aviation emissions in the EU ETS: Much ado about nothing? A review. *Transport Policy*, *17*(1), 38–46. https://doi.org/10.1016/j.tranpol.2009.10.010

Atsalakis, G. S. (2016). Using computational intelligence to forecast carbon prices. *Applied Soft Computing*, *43*, 107–116. https://doi.org/10.1016/j.asoc.2016.02.029

Borghesi, S., Montini, M., & Barreca, A. (2016). The European emission trading system and its followers: Comparative analysis and linking perspectives. Switzerland: Springer.

Brunton, S. L., Brunton, B. W., Proctor, J. L., Kaiser, E., & Kutz, J. N. (2017). Chaos as an intermittently forced linear system. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-00030-8

Brunton, S. L., Brunton, B. W., Proctor, J. L., & Kutz, J. N. (2016). Koopman Invariant Subspaces and Finite Linear Representations of Nonlinear Dynamical Systems for Control. *PLOS ONE*, *11*(2), e0150171. https://doi.org/10.1371/journal.pone.0150171

Chevallier, J. (2010). Volatility forecasting of carbon prices using factor models. *Economics Bulletin*, 30(2), 1642- 1660.

Decision 377/2013/EU on Derogating Temporarily from Directive 2003/87/EC Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community.

Derigs, U., & Illing, S. (2013). Does EU ETS instigate Air Cargo network reconfiguration? A model-based analysis. *European Journal of Operational Research*, *225*(3), 518–527. https://doi.org/10.1016/j.ejor.2012.10.016

Directive 2008/101/EC on Amending Directive 2003/87/EC So as to Include Aviation Activities in the Scheme for Greenhouse Gas Emission Allowance Trading within the Community.

Efthymiou, M., & Papatheodorou, A. (2019). EU Emissions Trading scheme in aviation: Policy analysis and suggestions. *Journal of Cleaner Production*, *237*, 117734. https://doi.org/10.1016/j.jclepro.2019.117734

Fan, X., Li, S., & Tian, L. (2015). Chaotic characteristic identification for carbon price and an multi-layer perceptron network prediction model. *Expert Systems with Applications*, *42*(8), 3945–3952. https://doi.org/10.1016/j.eswa.2014.12.047

García-Martos, C., Rodríguez, J., & Sánchez, M. J. (2013). Modelling and forecasting fossil fuels, CO2 and electricity prices and their volatilities. *Applied Energy*, *101*, 363–375. https://doi.org/10.1016/j.apenergy.2012.03.046

Gössling, S. (2020). Risks, resilience, and pathways to sustainable aviation: A COVID-19 perspective. *Journal of Air Transport Management*, *89*, 101933. https://doi.org/10.1016/j.jairtraman.2020.101933

Gössling, S., Humpe, A., Fichert, F., & Creutzig, F. (2021). COVID-19 and pathways to low-carbon air transport until 2050. *Environmental Research Letters*, *16*(3), 034063. https://doi.org/10.1088/1748-9326/abe90b

Guðbrandsdóttir, H. N., & Haraldsson, H. S. (2011). Predicting the Price of EU ETS Carbon Credits. *Systems Engineering Procedia*, *1*, 481–489. https://doi.org/10.1016/j.sepro.2011.08.070

Huang, Y., Dai, X., Wang, Q., & Zhou, D. (2021). A hybrid model for carbon price forecasting using GARCH and long short-term memory network. *Applied Energy*, *285*, 116485. https://doi.org/10.1016/j.apenergy.2021.116485

Koop, G., & Tole, L. (2012). Forecasting the European carbon market. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, *176*(3), 723–741. https://doi.org/10.1111/j.1467-985x.2012.01060.x

Koopman, B. O. (1931). Hamiltonian Systems and Transformation in Hilbert Space. *Proceedings of the National Academy of Sciences*, *17*(5), 315–318. https://doi.org/10.1073/pnas.17.5.315

Koopman, B. O., & Neumann, J. V. (1932). Dynamical Systems of Continuous Spectra. *Proceedings of the National Academy of Sciences*, *18*(3), 255–263. https://doi.org/10.1073/pnas.18.3.255

Larsson, J., Elofsson, A., Sterner, T., & Åkerman, J. (2019). International and national climate policies for aviation: a review. *Climate Policy*, *19*(6), 787–799. https://doi.org/10.1080/14693062.2018.1562871

Lee, D., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., Doherty, S., Freeman, S., Forster, P., Fuglestvedt, J., Gettelman, A., de León, R., Lim, L., Lund, M., Millar, R., Owen, B., Penner, J., Pitari, G., Prather, M., . . . Wilcox, L. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

Maertens, Grimme, Scheelhaase, & Jung. (2019). Options to Continue the EU ETS for Aviation in a CORSIA-World. *Sustainability*, *11*(20), 5703. https://doi.org/10.3390/su11205703

Malina, R., McConnachie, D., Winchester, N., Wollersheim, C., Paltsev, S., & Waitz, I. A. (2012). The impact of the European Union Emissions Trading Scheme on US aviation. *Journal of Air Transport Management*, *19*, 36–41. https://doi.org/10.1016/j.jairtraman.2011.12.004

Meleo, L., Nava, C. R., & Pozzi, C. (2016). Aviation and the costs of the European Emission Trading Scheme: The case of Italy. *Energy Policy*, *88*, 138–147. https://doi.org/10.1016/j.enpol.2015.10.008

Nava, C. R., Meleo, L., Cassetta, E., & Morelli, G. (2018). The impact of the EU-ETS on the aviation sector: Competitive effects of abatement efforts by airlines. *Transportation Research Part A: Policy and Practice*, *113*, 20–34. https://doi.org/10.1016/j.tra.2018.03.032

O'Connell, A., Kousoulidou, M., Lonza, L., & Weindorf, W. (2019). Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*, *101*, 504–515. https://doi.org/10.1016/j.rser.2018.11.033

Pavlenko, N., & Searle, S. (2021). Assessing the sustainability implications of alternative aviation fuels. International Council on Clean Transportation (working paper).

Rowley, C. W., Mezić, I., Bagheri, S., Schlatter, P., & Henningson, D. S. (2009). Spectral analysis of nonlinear flows. *Journal of Fluid Mechanics*, *641*, 115–127. https://doi.org/10.1017/s0022112009992059

Scheelhaase, J., Grimme, W., & Schaefer, M. (2010). The inclusion of aviation into the EU emission trading scheme – Impacts on competition between European and non-European network airlines. *Transportation Research Part D: Transport and Environment*, *15*(1), 14–25. https://doi.org/10.1016/j.trd.2009.07.003

Scheelhaase, J., Maertens, S., & Grimme, W. (2021). Options for improving the EU Emissions Trading Scheme (EU ETS) for aviation. *Transportation Research Procedia*, *59*, 193–202. https://doi.org/10.1016/j.trpro.2021.11.111

Scheelhaase, J., Maertens, S., Grimme, W., & Jung, M. (2018). EU ETS versus CORSIA – A critical assessment of two approaches to limit air transport's CO 2 emissions by market-based measures. *Journal of Air Transport Management*, *67*, 55–62. https://doi.org/10.1016/j.jairtraman.2017.11.007

Schmid P. J., & Sesterhenn J. (2008). Dynamic mode decomposition of numerical and experimental data. 61st Annual Meeting of the APS Division of Fluid Dynamics. American Physical Society, 2008.

Takens, F. (1981). Detecting strange attractors in turbulence. *Lecture Notes in Mathematics*, 366–381. https://doi.org/10.1007/bfb0091924

Vespermann, J., & Wald, A. (2011). Much Ado about Nothing? – An analysis of economic impacts and ecologic effects of the EU-emission trading scheme in the aviation industry. *Transportation Research Part A: Policy and Practice*, *45*(10), 1066–1076. https://doi.org/10.1016/j.tra.2010.03.005

Xu, H., Wang, M., Jiang, S., & Yang, W. (2020). Carbon price forecasting with complex network and extreme learning machine. *Physica A: Statistical Mechanics and Its Applications*, *545*, 122830. https://doi.org/10.1016/j.physa.2019.122830

Zhao, X., Han, M., Ding, L., & Kang, W. (2018). Usefulness of economic and energy data at different frequencies for carbon price forecasting in the EU ETS. *Applied Energy*, *216*, 132–141. https://doi.org/10.1016/j.apenergy.2018.02.003

Zhou, Y., Searle, S., Pavlenko, N. (2022). Current and future cost of e-kerosene in the United States and Europe. International Council on Clean Transportation (working paper).

Zhu, B. (2012). A Novel Multiscale Ensemble Carbon Price Prediction Model Integrating Empirical Mode Decomposition, Genetic Algorithm and Artificial Neural Network. *Energies*, *5*(2), 355–370. https://doi.org/10.3390/en5020355