The impact of the EU-ETS on the aviation sector: Competitive effects of abatement efforts by airlines

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ABSTRACT

In the next few years, it is estimated that the aviation sector will account for more than 15% of total GHG emissions against the current 5%. In order to curb emissions and, considering the rapid growth of this industry Directive 101/2008/EC has included the aviation sector in the European Union Emission Trading Scheme (EU-ETS), thus generating additional costs for airlines. This paper develops an original model to analyse the impact of EU-ETS on the aviation sector. This study expands previous researches by explicitly considering abatement efforts in the airline cost function, by highlighting interdependence effects using strategies to reduce emissions, firms in the secondary market, free allowances, and fines. Several policy implications, which are particularly useful in an operational perspective, can be derived to support policy-making decisions through a better understanding of the overall EU-ETS effects. The pattern of results suggests the presence of a trade-off in determining profits between the efficiency cost of individual airlines and the share of allowances distributed free of charge. From a regulatory industrial perspective, the higher the latter, the lower the incentives for airlines to reduce GHG emissions. Moreover, the higher is the number of airlines competing on the same air route, the lower is the increase of profits under a Cournot oligopoly, and/or a market collusion structure. Still pending is the final effect of different strategies adopted by airlines in the allowance market.

1. Introduction

The aviation industry is still under a rapid expansion worldwide. Over the past 40 years, the global air travel volume has increased tenfold, recording a rate of growth three times higher than the world’s economy (IATA, 2011). Annual growth in global air transport is expected to last at around 5% until 2030. The persistent increasing demand for flights has been driven by several factors, such as the intensification of worldwide flows of trade, the rise of mass tourism, especially from emerging countries, and the continuous changes in consumers’ behaviour (Gössling et al., 2012). Moreover, the deregulation and liberalisation policies that have concerned the sector since the 1990s have encouraged new competitors, largely low-cost carriers, to enter the market, increasing pressure on air fares and, also, making air transport accessible to individuals with tighter budgets (IATA, 2007; Meleo et al., 2016). This trend is confirmed by the positive growth rate of air transport passengers in the European Economic Area (EEA) (+ 25% in 2010–2016), less obvious in large countries. In the sole European Union (EU), the number of flights increased by 80% in the period 1990–2014, with an
expected 45% growth between 2014 and 2035 (EASA, 2016).

This means a strong impact on climate change, since emissions from aviation are estimated to account for around 13% of total transport greenhouse gas (GHG) emissions, and around 3.3% of the total European CO₂ emissions (European, 2017), persisting the aviation sector as the main source of air pollution. According to the base scenario of EASA (2016), while progress is being made in increasing aircraft engine efficiencies, and reducing the emission rates, future technology improvements are unlikely to balance the negative effect of the forecasted traffic growth, and CO₂ emissions in 2035 are expected to be 44% higher than those in 2005.

To reduce aviation GHG emissions, the Directive 101/2008/EC has included the airline industry in the European Union Emission Trading Scheme (EU-ETS), the biggest worldwide emission trading scheme launched on January 1st, 2012. The resulting political and legal debate has induced the European Commission (EC) to amend the Directive. Firstly, it enforces with Decision 2013/337/EU, temporarily suspending the application of the ETS to airlines operating flights from or to non-EU destinations (the so-called “stop the clock” derogation), then, with the Commission Regulation 2014/421. In October 2016, the International Civil Aviation Organisation (ICAO) decided to implement a global market based measure, starting from 2021 in order to regulate international aviation emissions, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The scheme aims at stabilising CO₂ emissions at 2020 levels, by requiring airlines to monitor their emissions on all international routes, and to buy offset credits to compensate part of future emission growth above 2020 levels (ICAO, 2016). The first two phases of CORSIA (pilot and first phase) will run from 2021 to 2027, and shall be made on a voluntary basis (Schep et al., 2016). In December 2017, coherently with the Resolution adopted by ICAO, the European Commission has extended until December 31st, 2023 the current derogation from the EU-ETS obligations for flights to and from third countries (Commission Regulation 2017/2392). As a result, EU-ETS currently covers all flights arriving in or departing from EEA, regardless of the airline nationality (Meleo et al., 2016).¹

One of the most debated issues is the EU-ETS effect on market functioning and on airline competitiveness, due to additional costs airlines must bear in order to comply with the Directive (Kopsch, 2012). The thorough understanding of airline compliance to EU-ETS is crucial, so that the current scheme can be better fine-tuned, to be eventually implemented worldwide (Li and Tang, 2017). It is also important to evaluate, from efficiency and in environmental perspectives, how airlines might modify their supplies (Cui et al., 2017; Qiu et al., 2017). While the efficiency concerns the opportunity to adopt least-cost regulatory measures, the environmental effectiveness involves attainment of GHG emissions planned reductions. Changes in routes, as well as in networks, services and departure schedules frequencies on each route operated by single airlines, may also affect final consumers demand, especially when those routes are crucial for the economic development of the served region, when public served obligations are imposed (Wittman et al., 2016; Calzada and Fageda, 2014).

The economic literature has thoroughly investigated the EU-ETS effects on economic performance, competitiveness, innovation (see Ellerman et al., 2015; Martin et al., 2015; Brink et al., 2016). Focusing on the aviation sector, some authors have found that EU-ETS might generate a reduction on profit margins (Malina et al., 2012; Girardet and Spinler, 2013), a loss of market share, and potential reduction of growth rates (Faber and Brinke, 2011; Anger and Köhler, 2010). These effects may be even more important when airlines cannot offset environmental costs, passing additional costs to air fares or using profits earned on extra-European routes.² On the other hand, further studies have focused on the incentives provided by EU-ETS to invest in environmental friendly solutions (Sgouridis et al., 2011; Sheu and Li, 2013). They stress that airline innovation effort is rather limited, compared to other industries, as it relies mainly upon technological efficiency (i.e. modernising the fleet to incorporate more fuel-efficient airlines), operational efficiency (i.e. engine washing, less use of auxiliary power units), and alternative fuels introduction (Cui et al., 2016; Li et al., 2016).

The environmental effects, even if positive, are still too limited (Anger and Köhler, 2010; Vespermann and Wald, 2011; Malina et al., 2012; Chin and Zhang, 2013), possibly because the climate impact on aviation is not entirely caused only by CO₂ emissions (Dessen et al., 2014; Preston et al., 2012).

Only few studies have formally assessed actual and potential EU-ETS effects on airlines competition. Barbot et al. (2014) show that EU-ETS may affect potential competition since the share of capped allowances, allocated initially for free, may be used by incumbent air operators as a strategy to deter new entries into the market. Chin and Zhang (2013) use a Cournot-Nash model to assess changes in the output and efficiency level, due to differences in allowance allocation methods. They emphasise an increase in both, profits and operating costs for airlines. While focusing on competitive effects, changes induced by the emission trading scheme on abatement efforts have not yet been explicitly considered in equilibrium modelling. Low carbon technologies and higher energy efficiency levels drive positive impacts on investments, and are likely to remain one of the main factors explaining the adoption of market-based measures addressing GHG emissions. In order to fill the gap, this paper proposes an extension of current models exploring how the market equilibrium may change because of airlines strategies, due to incentives provided by EU-ETS and different regulatory designs.

Starting from the study by Chin and Zhang (2013), and the model developed by Meleo et al. (2016), the paper provides a new generalisation of the Cournot-Nash equilibrium to n firms focusing on different equilibrium solutions that airlines could achieve given additional costs and efficiency incentives provided by their EU-ETS inclusion. In order to explicit changes in abatement efforts, generated by the emission-trading scheme, an additional component to the cost function has been introduced. More specifically, in

¹ First of all, the derogation stated that all flights within EEA were part of EU-ETS regulatory design, and the residual ones were under exemption until 2013. Starting from 2014, all flights have been under EU-ETS, including those outside EEA, but only for the amount of kilometers travelled within this area.
² This is the case of Ryanair carrier that announced and enforced the pass through strategy charging passengers with an extra-fare of 0.25 Euros per flight (Elsworth and MacDonald, 2013).
the unitary cost function of airlines a new variable is included, so-called abatement effort, representing all those investments specifically determined to reduce emissions, such as purchase of more fuel-efficient planes, and optimisation of routes. Different competitive assumptions regarding market structure and airlines behaviour are considered, namely perfect collusion (monopoly), and deviation from collusion, both in the case of homogeneous and heterogeneous firms (Alderighi and Piga, 2010).

The theoretical results on output, profit and mitigation efforts have been tested on Italy, as an applied case, since it is one of the major air transport markets in EU, both for number of passengers, and volume of freight and mail. Italian airlines, already facing difficulties in adapting themselves to the new regulatory framework, implementing the necessary improvements to operate more efficiently, may provide an interesting case to evaluate the EU-ETS impact on the heterogeneous firms. Like other European countries, Italy experienced significant changes in the past fifteen years (OECD, 2014). In the period 2001–2015, almost 157 million passengers transited through Italian airports with a growth of 74.5%. As a consequence, GHG emissions increased by 19.1% from 1990 to 2014, according to ISPR (2016). They currently represent about 1.8% of the national total emissions from transport, and about 0.5% of the Italian GHG total.

Several implications can be collected to operatively support policy-making decisions through a better understanding of the overall EU-ETS effects. The results highlight the presence of a trade-off in determining profits between the efficiency cost of individual, carriers and the share of allowances distributed free of charge. From a regulatory perspective, the higher the latter, the lower are the airline incentives to reduce GHG emissions. Moreover, the higher the number of carriers competing on the same air route, the lower is the increase of profits under a Cournot oligopoly, and/or a market collusion scheme. The effect of different possible strategies adopted by airlines is still pending in the allowance market, given the high number of variables involved in the decision-making process.

The paper is organised as follows. Section 2.1 describes the regulatory background, enhancing the functioning of the aviation sector under the EU-ETS. Section 2.2 discusses the methodology applied for developing the model. Section 3 derives multiple market equilibria for both homogenous (Section 3.2) and heterogeneous (Section 3.2) airlines, under different competitive assumptions, and potential competitive EU-ETS effects, simulating the model on the Italian case (Section 3.3). Finally, Section 4 provides further policy suggestions and extensions.

2. Background and methods

2.1. The basics of EU-ETS aviation

Many countries around the word have implemented EU-ETS as one of the most cost-efficient ways to control GHG emissions (Li and Tang, 2017). The aviation sector have been included in the scheme since January 1st, 2012, as introduced in Section 1. These rules, initially set by Directive 2008/101/EC, stated that all flights departing from and arriving at an EEA airport must be covered by emission permits, regardless of the country in which the airline is registered. This means that also extra-European companies should have complied within this EU-ETS framework.

After the fierce debate that followed the introduction of this regulation, the EC decided to amend this Directive by Decision 2013/337/EU, and, later on, by Regulation 2014/421. The EU-ETS is currently enforced only for flights within EEA until 2023, while waiting for a global agreement that shall come into force under ICAO supervision.

As known, the EU-ETS is a market-based instrument for environmental management, working as a “cap and trade” system designed to avoid possible negative externalities, due to the overproduction of pollutants above the theoretical social optimum level. It is able to provide an economic incentive in terms of profits and volume of business activities. It adopts a top-down mechanism already applied for industrial plants and sectors (Baumol and Oates, 1988; Ryan et al., 2011; Rydge, 2015), though the emission cap sets by the EC. In 2012, the EC distributed a number of permits corresponding to 97% of the average aviation sector emissions registered in Europe (2004–2006), with the cap slightly reduced to 95% (2013–2020). In respect to the allocation method, in 2012, again, 15% of the total permits issued by the EU were auctioned with a bidding process, and 85% distributed for free. In 2013–2020, 82% of the cap shall be allocated free of charge, 15% by auctions, and 3% collected in the new entrants’ reserve. As a result, for each year between 2017 and 2020, aircraft operators would receive the same number of allowances as in 2016.

Once the cap has been set, the system is implemented at Member State level: every aircraft operator is linked to an “administering Member State” which corresponds to the country where the company is registered, or to the European State where the aircraft operator registers the highest number of flights. In respect of auctioned permits, Directive 2008/101/EC states that, starting in 2012, the emissions to be considered for each Member State are those recorded in 2010, and, for the following years, emissions registered 24 months before the auctioning base-year.

Different regime for the allowances distributed free of charge, where the EC follows a benchmark based approach. Emission permits to be assigned are fixed, and obtained as a certain number of allowances due for every tonne-kilometre (TKM). Therefore, the aircraft operators receive from the competent Member State EU-ETS authority a number of emission permits obtained by multiplying the benchmark factor by the TKM registered in each specific period.

By 30th April of each year, every airline operator must return emissions to the national competent authority of the administering Member State. In case of deficit, airlines must buy the lacking allowances on the carbon market: otherwise, they shall incur in a penalty of 100 Euros per tonne of CO₂ emissions. In addition to this penalty, airlines must purchase in any case the allowances not surrendered.

The current regulatory design is formalised in the next section in terms of airline cost functions and related payoffs.
∀ = …

Given a certain e, allowances are allocated among airlines. This second phase outlines the time in which the EU-ETS incentive mechanisms are necessary to reduce emissions by one pollution unit. Let the ETS Directive, in addition to those typically related to operational activity, like time constraints from boarding process to air control. Once the permits have been issued, airlines compare carbon price with marginal abatement cost (MAC), i.e. the marginal cost of operators, characterized by the presence of significant entry barriers discouraging potential competitors from adopting entry strategies (Barbot et al., 2014; Calzada and Fageda, 2014). As a result, the aviation sector typically assumes an oligopolistic structure, rather than a perfect competitive one, and firms compete over the share of flights and of TKM flown during the year (Chin and Zhang, 2013).

In this paper, the aviation market is modelled via a simultaneous Cournot game where firms compete on the share of TKM flown during the year, as generally assumed by both theoretical (Barbot et al., 2014; Basso, 2008; Chin and Zhang, 2013; Verhoef, 2010) and empirical economic literature (Brander and Zhang, 1990; Oum et al., 1993). The aviation industry is designed to be composed of n aircraft operators, with n limited to be such that a competitive market structure is not feasible. Each airline operator maximizes its own profits choosing the level of output in terms of TKM flown (namely qi, ∀ i = 1, …, n), given a certain efficiency level (e). The latter describes the increase in efficiency resulting from GHG emission abatement efforts, that individual airlines make in order to comply with the EU-ETS system. The abatement effort includes any investment intended to reduce emissions, i.e. the purchase of a more efficient aircraft engine, the reduction of emission rates from engines, the optimization of air routes, etc. Moreover, the aviation industry is assumed to be a net buyer of allowances, and the carbon price and sanctions are counted as exogenous variables (Anger and Köhler, 2010).

Secondly, the EU-ETS Directive identifies two different phases. The first one, which involves computation of the historical emissions, to set the cap, named the “benchmark period”, while the other, “EU-ETS period”, refers to the moment in which free allowances are allocated among airlines. This second phase outlines the time in which the EU-ETS incentive mechanisms effectively start to operate, inducing changes in the aviation market. Airlines compete managing simultaneous constraints imposed by the EU-ETS Directive, in addiction to those typically related to operational activity, like time constraints from boarding process to air control. Once the permits have been issued, airlines compare carbon price with marginal abatement cost (MAC), i.e. the marginal cost necessary to reduce emissions by one pollution unit. Let’s assume a typical airline ith, producing emissions exceeding the amount stated in this permit issued. If the carbon price is lower than the MAC, then this airline shall buy permits from the market to offset its target. On the contrary, if the carbon price is higher than the MAC, then the airline strategy is likely to invest in innovation to reduce emissions. Finally, airlines can sell the permits that exceed their actual emissions, and thereby earn a profit. This incentive scheme implies that airlines should consider in their cost function some additional varying components, the allocation method applied (% of emission permits grandfathered and auctioned), the amount of investments made to reduce emissions, and carbon price.

Thirdly, as suggested by several studies (Barbot et al., 2014; Basso, 2008; Brander and Zhang, 1990; Chin and Zhang, 2013; Girardet and Spinler, 2013; Oum et al., 1993; Verhoef, 2010), it is assumed that the aviation market is characterized by an inverse linear demand function:

\[ P(Q) = a - bQ \]

where P is the price, and Q is the quantity demanded by consumers. Moreover, \[ Q = \sum_{j=1}^{r} q_j \] identifies the total quantity supplied by

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**Table 1**


Source: Statistical pocketbook 2017 - European Commission.

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<td>129,668</td>
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<td>125,165</td>
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<td>107,892</td>
<td>106,082</td>
<td>138,431</td>
<td>142,016</td>
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<td>TR</td>
<td>21,318</td>
<td>47,950</td>
<td>106,913</td>
<td>119,372</td>
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<td>5</td>
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<td>31,205</td>
<td>72,149</td>
<td>103,733</td>
<td>113,184</td>
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<td>6</td>
<td>KLM Royal Dutch Airlines</td>
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<td>68,322</td>
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<td>91,477</td>
<td>93,228</td>
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<td>51,242</td>
<td>42,686</td>
<td>48,564</td>
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<tr>
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<td>DE</td>
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<td>49,270</td>
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<td>21,164</td>
<td>29,522</td>
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<td>SAS Scandinavian Airlines</td>
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<td>30,119</td>
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<td>19,222</td>
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<td>21,445</td>
<td>24,775</td>
</tr>
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</table>
airlines in terms of flights offered by the aviation industry (i.e. n producers). Even if this hypothesis is widely accepted in the economic literature, it is worth noting that the linearity assumption neglects the role played by air mail and air freight traffic, and does not differentiate passenger demand distinguishing business, tourism and low-cost passengers, thus losing information on passengers’ reactions to price variations.\(^3\)

Finally, the standard homogeneous quadratic unitary cost function is assumed to better adapt airlines strategy (Barbot et al., 2014; Clemenz, 2010; Dijkstra and Rübbelke, 2013). With respect to the aviation sector, and according to the specific functioning of the EU-ETS, this unitary cost function depends on the abatement efforts made to improve efficiency (ε), and on marginal cost (α) that is independent from ε itself, i.e. the amount of all the other variables’ unitary costs that are uncorrelated with the effort. Hence, each unit of effort increases more than proportionally the airline costs via the following unitary cost function:\(^4\)

\[
c_i (ε) = α + βε_i^2 \quad \forall \quad i = 1, \ldots, n.
\]  

(1)

where \(α, β \geq 0\) reflect the assumption of homogeneity among airline operators, given that they are not indexed by \(i\), and \(ε_i\) assumes non-negative values, i.e. \(ε_i \geq 0\). Relaxing this assumption, \(β\) could be also firm specific (\(β_i\)) to adapt different abatement effort policies for emission reduction among heterogeneous airlines. Hence, the efficiency level \(ε_i\), chosen by the airline \(i\) and defined as the ratio between TKM and the quantity of fuel consumed, could encompass different abatement effort strategies. European airlines are, for instance, increasingly replacing conventional petroleum-based liquid jet fuels, such as kerosene or naphtha, with advanced liquid biofuels in order to reduce CO\(_2\) emissions and energy consumption (Telkamp, 2012). Under this policy, the abatement effort would be simply equal to the price differential between biofuels and conventional ones, possibly weighted in \(ε_i\) to take into account other abatement effort strategies adopted by airlines.

Under these assumptions, in the benchmark period (denoted with the subscript \(B\)), the profit function for a generic \(i\)th airline is:

\[
π_{iB} = \left( a - b \sum_{j=1}^{n} q_{iB}^j \right) - (\alpha + βε_i^2)q_{iB}.
\]

(2)

Differently, in the EU-ETS period (denoted with the subscript \(E\)), the profit function for the \(i\)th airline is:

\[
π_{iE} = \left( a - b \sum_{j=1}^{n} q_{iE}^j \right) - (\alpha + βε_i^2)q_{iE} - f(q_{iE}, ε_i, P, δ)
\]

(3)

with

\[
f(q_{iE}, ε_i, P, δ) = \Delta \left( \frac{q_{iE}}{ε_i} \sum_{j=1}^{n} q_j^E \right) - \frac{q_{iB}}{ε_i} \sum_{j=1}^{n} q_j^B
\]

(4)

where \(\Delta = (P_δ + P_ε δ_m + P_δ - P_ε δ_s)\).

Eqs. (3) and (4) well reflect airline strategies under the EU-ETS: \(f(\cdot)\) includes the case in which permits are purchased by auction (\(a\)) or on the carbon/secondary market (\(m\)), as well as the situation in which airlines incur fines (\(r\)) or sell the permits in the presence of a surplus, given vectors \(P = [P_a, P_m, P]\) and \(δ = [δ_m, δ_e, δ_s]\).

In details, \(P_a\) and \(δ_m\) are respectively the auction price and the percentage share of permits purchased from auctions, \(P_m\) is the allowances market price that the \(i\)th airline has to pay on the carbon market in case of allowances deficit, and \(δ_m\) is the share of permits that are bought on this secondary market. Lastly, \(P_r\) and \(δ_e\) refer to the unitary sanction enforced on non-compliant companies and the amount of allowances not returned to the EC. Since allowances must be surrendered in any case, even after the payment of the sanction, the price \(P_r\) is twofold. It is composed of the unitary sanction \(s\), and of the unitary market price \(P_m\) that shall be paid by the non-compliant airline to buy permits in order to cover these additional emissions at a certain future time \(t^*\), i.e. \(P_r = s + P_m t^*\).

As noticed, Eq. (4) includes also the case in which airlines record a surplus in allowances that can be sold in the carbon market to gain a profit. In detail, \(δ_s\) is the rate of permits sold at the market price \(P_m\). Finally, \(γ\) represents the quota of free allowances allocated to the airline, according to emissions recorded in the benchmark period \(B\) as described in Section 2.

Given the relationship among variables mentioned above, \(δ_i = \delta_a - δ_m - \delta_e\), the following conditions must be true: \(δ_a \in [0,1]\), \(δ_m \in [0,1]\), \(δ_e \in [0,1]\) and \(δ_s \in [0,1]\). In particular, \(δ_a\) equals to 0 when the airline has a deficit, which means that it is polluting more than the quantity of free of charge allowances, while \(δ_e > 0\) if and only if \(\frac{q_{iE}}{ε_i} \sum_{j=1}^{n} q_j^E < 0\) with \(δ_m = δ_a = δ_e = 0\).

Finally, the second term of Eq. (4) represents the amount of emissions not covered by the allowances allocated for free. In particular, as suggested by Chin and Zhang (2013), the \(i\)th airline has \(\frac{q_{iB}}{ε_i}\) of permits to comply with the regulation.\(^5\)

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\(^3\) The aviation demand literature (Gillen et al., 2007; Brons et al., 2002) develops and reviews specific demand functions for each group of consumers with the aim of accounting for their different behaviours due to price changes.

\(^4\) The linearity of the cost function to the square efficiency level results clear from Eq. (1).

\(^5\) See Meleo et al. (2016) for details and a brief description of the model applied to the EU-ETS estimations and simulations with respect of costs, revenues, and welfare in airlines industry.
Under this model, which also covers airlines with a deficit in allowances, the following simplifying assumption could be made: \( \delta_s = \delta_h = 0 \). The latter induces \( \delta_m = 1 - \delta_i \) and \( \Delta = \delta_m (P_m - P_i) + P_i \). In this respect, emission permits are not generally sold through auctioning in most Member States, apart from Germany, United Kingdom and Poland.

The next section derives market equilibria, for homogenous and heterogeneous airlines, and potential competitive EU-ETS effects, considering efficiency incentives provided by the mechanism.

3. Results and discussions

3.1. Homogeneous firms

The analysis first describes the different equilibria in the aviation sector applying the Cournot-Nash framework (Dutta, 1999; Gibbons, 1992) before and after the introduction of the EU-ETS. It distinguishes the benchmark period (B), and the EU-ETS period (E).

The following proposition results in equilibrium for period B.

**Proposition 1.** In the Cournot-Nash equilibrium for the benchmark period (B), the payoff for the \( i \)th airline company is equal to

\[
\pi_{iB} = \frac{1}{(n + 1)^2} (a - \alpha)^2 \quad \forall \ i = 1,...,n. \tag{5}
\]

The enforcement of the EU-ETS, to mitigate global warming, induces some changes in the cost function and in the airline abatement effort, observable in the equilibrium following the second proposition (Appendix A provides proofs of Propositions 1 and 2).

**Proposition 2.** In the Cournot-Nash equilibrium for the EU-ETS period (E), the payoff for the \( i \)th airline company is equal to

\[
\pi_{iE} = \frac{(a - \alpha - \gamma)^2}{(n + 1)^2} + \frac{\Delta \gamma}{n} \quad \forall \ i = 1,...,n;
\]

with \( \Delta = (P_0 \delta_0 + P_m \delta_m + P_i \delta_i - P_n \delta_i) \) and \( \gamma = \frac{1}{2} \sqrt{\frac{\Delta^2}{1}} \)

Under the EU-ETS, the optimal quantity is reduced by \( g_\Delta \), and increased by \( g^2_\Delta \). Increases in the unitary cost of the abatement effort made by the firm \( \beta \) as well as in \( \Delta \), the variable which summarizes the EU-ETS cost, contribute to increase \( g_\Delta \) and, indirectly, reduce \( \pi_{iE} \). In general, the \( \Delta \) component has a twofold effect. In addition to the negative effect in terms of output and profit reduction, it induces a positive variation on profits, according to the percentage of free allowances (\( \gamma \)) assigned to airlines. Intuitively, the bigger is the share of allowances distributed free of charge to the airlines, the greater are the company profits (if \( \Delta > 0 \)), i.e. the overall effect of \( \Delta \) depends on the magnitude of emissions allocated free of charge.

In equilibrium, the optimal abatement effort is greater than zero and equal to \( \sqrt[1/2]{\frac{\Delta}{2}} \). Hence, if the allowance price \( P_n \) increases on the carbon market, the abatement effort grows proportionally to compensate effects of such variation, especially under the simplifying assumptions mentioned in Section 2.2. The CO\(_2\) emission allowance price (\( P_m \)), on one side, could encourage higher level of airline efficiency\(^6\) and, on the other, could affect profits via \( \Delta \) and \( g_\Delta \). If \( P_m \) increases, holding other parameters fixed, \( \Delta \) and \( g_\Delta \) differ less than proportionally as well as profits.

The EU-ETS profit results to be higher than the benchmark one if and only if the following condition holds:

\[
n g_\Delta [\gamma - 2(a - \alpha)] + (n + 1)^2 \gamma \Delta > 0 \quad \text{i.e.} \quad \gamma > \frac{n g_\Delta [2(a - \alpha) - \gamma]}{(n + 1)^2 \Delta} = \gamma^*.
\]

This occurs when the share \( \gamma \) of free allowances is greater than the threshold \( \gamma^* \). The effects on CO\(_2\) emission allowance price (\( P_m \)) and related simulations under different competitive assumptions are presented in Appendix D. Fig. 3 exhibits simulated effects on main model parameters under the Cournot oligopoly. In particular, EU-ETS costs (\( \Delta \)), the efficiency level related to the abatement effort (\( \alpha \)), profits (\( \pi_{iE} \)), the threshold of allowances free of charge (\( \gamma^* \)) and the combined effect of prices and EU-ETS costs (\( g_\Delta \)) are considered.

To fully understand the competitive influence of the EU-ETS, changes in equilibria are evaluated when airlines decide to cooperate, for instance through a cartel, rather than compete. The difference between the collusive outcome and the Cournot’s best response solution is that airlines are aware that their profits depend on total TKM offered. Consequently, they shall behave as a monopolist in maximizing their profits (see Propositions 3 and 4 in Appendix B).

Comparing Cournot oligopoly and collusion equilibria, it is worth noting that differences do not refer to the design of the emissions trading scheme. Although EU-ETS affects outputs and profits, the equilibrium depends on the number of firms operating in the market and the demand elasticity.

Finally, optimal output, price and profits are derived in the case of perfect collusion with only one firm deviating. As a result, the collusive outcome is not achieved because of the deviation from the cartel of the \( j \)th airline. The latter has to maximize its profit, given that the remaining \( n-1 \) airlines will still produce the monopoly output (see Proposition 4 and the relative proof in Appendix C).

\(^6\) Note that it enters directly in the airline reaction curve.
Table 2
Summary payoffs in equilibrium according to different competitive assumptions.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Before EU-ETS</th>
<th>After EU-ETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cournot oligopoly</td>
<td>( \pi_{i,B} = \frac{1}{a+b} (a-\alpha)^2 )</td>
<td>( \pi_{i,E} = \frac{(a-n-k\Delta)^2}{(a+n+1)^2} + \frac{k\Delta}{n} )</td>
</tr>
<tr>
<td>Collusion</td>
<td>( \pi_{j,B} = \frac{(a-\alpha)^2}{4ab} )</td>
<td>( \pi_{j,E} = \frac{(a-n-k\Delta)^2}{(a+n+1)^2} + \frac{k\Delta}{n} )</td>
</tr>
<tr>
<td>Deviation of the ( j )th firm</td>
<td>( \pi_{j,B} = \frac{(a+n+1)(a-\alpha)^2}{8ab} )</td>
<td>( \pi_{j,E} = \frac{(a-n-k\Delta)^2}{16n^2} + \frac{n\Delta}{n} )</td>
</tr>
</tbody>
</table>

With respect to the Cournot equilibrium, the main difference is a profit reduction for the airline that chooses to deviate from the collusion design. The remaining \( n-1 \) operators still behave as a unique monopolist, in the sense that they are nevertheless part of a cartel. Thus, the deviation from the collusion is not profitable. Profits are lower than those in monopoly, especially for the \( j \)th firm that decides not to take part in the collusion. Hence, this strategy is dominated by the monopolistic one.

Table 2 summarises payoffs respectively for the benchmark (B) and the EU-ETS (E) periods under three different market structures. Figs. 4 and 5 show the effects on main model parameters of the CO2 emission allowances price and the share of free of charge allowances. Given a fixed secondary market price, profits increase linearly, according to the variation of the share \( (\gamma) \) of allowances free of charge. If also prices increase, especially under collusion and deviation assumptions, profits also increase exponentially.

3.2. Non-homogeneous firms

Propositions 1 and 2 can be extended by relaxing the homogeneity assumption (Alderighi and Piga, 2012; Alderighi and Piga, 2010) and allowing, without loss of generality, two distinct types of airlines \( r = 1,2 \), among the \( n \) characterising the Cournot oligopoly.

Specifically, there is a first homogeneous infra-group \( (r = 1) \) composed of \( k \cdot n \) firms, with \( k \in [0,1] \), while the remainings belong to the second group \( (r = 2) \). Profit functions in the two periods differ among groups, given a specific structure of marginal costs. The latter depend on values of \( \alpha_r \) and \( \beta_r \). In detail, they are respectively equal to

\[
\pi_{i,B} = \left( a-b \sum_{j=1}^{n} q_{j,B} \right) q_{i,B} - (\alpha_r + \beta_r \epsilon_{i,B}^2) q_{i,B} \\
\pi_{i,E} = \left( a-b \sum_{j=1}^{n} q_{j,E} \right) q_{i,E} - (\alpha_r + \beta_r \epsilon_{i,E}^2) q_{i,E} - f \left( q_{i,E}, \epsilon_{i,E}, \beta, \delta \right).
\]

(7)

Thus, Proposition 1 can be extended by identifying distinct profit functions for the two groups and considering \( \epsilon_{i,B} = \frac{1}{2} \sqrt{2\Delta^2 \beta} \) with \( i = 1,2 \)

\[
\pi_{i,B,1} = \frac{1}{a+b} (a-\alpha_1-k(1-k)\alpha_2) \quad \forall \; i = 1,...,kn, r = 1 \text{ and} \\
\pi_{j,B,2} = \frac{1}{(a+b)^2} (a-\alpha_2-nk(\alpha_2-\alpha_1)) \quad \forall \; j = 1,...,(1-k)n, r = 2
\]

and Proposition 2 can be characterized to adapt to heterogeneity in the following way:

\[
\pi_{i,E,1} = \frac{(a-\alpha_1-k\Delta_1-n(1-k)(\alpha_1-\alpha_2))}{(a+n+1)^2} + \frac{a-k(1-k)\alpha_1}{n(a-k\Delta_1-(1-k)\alpha_2)} \Delta y \\
\pi_{j,E,2} = \frac{(a-\alpha_2-k\Delta_2-nk(\alpha_2-\alpha_1))}{(a+n+1)^2} + \frac{a-k(1-k)\alpha_2}{n(a-k\Delta_2-(1-k)\alpha_1)} \Delta y
\]

\( \forall \; i = 1,...,kn \text{ and } j = 1,...,(1-k)n. \)

Reaction curves and optimal outputs are derived by maximizing profits in Eq. (7) to extend Propositions 1 and 2 (see for details Appendix A). Fig. 6 shows how homogeneous and heterogeneous airlines profits vary according to different values in prices of CO2 emission allowances. Changes in profits are higher, in absolute values, for heterogeneous airlines. Moreover, the more airlines are uniformly distributed between the two heterogeneous groups (with low and high abatement efforts, respectively), the greater the impact on profits. Heterogeneous airlines also exhibit higher profits variations compared to homogeneous ones.

3.3. An empirical simulation: the effect of the EU-ETS on Italian airlines

Modelling equilibria for Cournot results, outputs, profits, and efficiency incentives are simulated at national level focusing on Italian airlines. Italy is a particularly challenging case-study since Italian carriers are encountering more difficulties than most of the other European competitors in adapting themselves to the new regulatory framework. Apart from the worldwide well-known Alitalia...
case, other national carriers have suffered a progressive market share erosion, because of their decreasing competitiveness on served routes. In 2015, there were only two airlines with an Air Operator Certificate issued by the Italian Civil Aviation Authority (ENAC), among the top ten airlines in terms of total passengers operating in Italy. In respect of the domestic market, the share of Italian carriers is larger, and shows five national airlines in the first ten positions.

Even in Italy, where growth rate of air transport passengers is lower than EEA average (+25% in 2010–2016), growth is still positive (Fig. 1). Even though, Italian GHG emissions are higher then European average. The Italian airlines competitive position shows a rather interesting case to analyse how additional costs faced by firms in coping with EU-ETS, potentially affect market equilibrium and abatement efforts. In this section, the analysis is addressed to selected Italian carriers with an Air Operator Certificate issued by the ENAC. Given the almost total lack of detailed data on operational activities for single routes – in terms of service frequency, departure schedule, associated efforts and costs – simplified assumptions when applying the model have been considered.

Firstly, following recent contributions (Chin and Zhang, 2013), TKM emissions are used as proxy for the quantity supplied by airlines in order to capture potential EU-ETS effects. Secondly, in respect of the only Italian carriers, domestic market might not be fully covered by this evaluation, since all airlines certificated by other European authorities are excluded. Provided that airlines directly compete only with those that offer flights on same routes, and on an airport sustainability base.7 It is implied that, being the number of airlines on single routes generally limited, they are properly modeled via a Cournot oligopoly. Finally, given the previously developed theoretical model, a inverse linear demand function8 is discussed.

To adapt the general framework of non-homogeneous firms, Italian airlines are identified through a cluster analysis9 based on accountability data extracted from the Bureau van Dijk’s AIDA database. Italian aviation sector under the EU-ETS results in two main groups: the first one Alitalia, Siro and Air Dolomiti, the second group all the other seven remaining carriers. This is evident when a hierarchical cluster analysis is performed, in respect of 2013 data on verified emissions, earnings, EBITDA, and the free allowances received by the top ten airlines (see Fig. 2). Clusters have been constructed on the Euclidean distance matrix, computed on standardised company variables, and applying the Ward method. Scaling variables, accurately selected for this analysis, two groups with cardinality greater than 1 have been identified. This is suitable whenever a heterogeneity discussion is addressed.10

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7 Competition authorities adopt the approach of the point-of-origin/point of destination pair approach (“O&D”) to define relevant markets in air transport of passengers.

8 In this case, the slope $b$ is not normalized to be equal to 1, differently from Barbot et al. (2014) and Chin and Zhang (2013). For the purpose of this section, fixing $b = 1$ seems to be too unrealistic according to the discussion proposed in Section 2.2 and in Anger and Köhler (2010). Even less powerful for real data explanation, interesting is the description of the model parameter variations effects resulting from the assumption of $b = 1$, which will induce a loss of generality, given a too high demand variation on a just small change in prices.

9 Cluster analysis ensures to identify similar structure within the data, determining homogeneous groups of airlines within the cluster, i.e. aminimising with-in deviance and a maximising infra-group deviance. The dendrogram is a graphical representation of the latent hierarchy behind observations, useful to recognise the appropriate number of clusters.

10 These two clusters result to give more information for our analysis purpose than the case in which a company is simply isolated (outlier) from the rest of the sector.
The Italian airlines heterogeneity is modeled assigning, as an example, the selected values to the following parameters:

\[ \alpha_i = 0 \text{ for } i = 1, \ldots, 10; \quad k = \frac{1}{10} = 0.3; \quad \beta_i = 1 \text{ (for } j = \text{Alitalia, Siro, Air Dolomiti), and } \beta_i = \frac{1}{2} \text{ for the remaining } n-k = 7 \text{ companies.} \]

Constant and null marginal operating costs \( \alpha_i \) are assumed to focus on the EU-ETS key factors. Moreover, partially following Barbot et al. (2014), the quadratic cost is a function of the abatement effort \( \beta_i e_i^2 \):

\[ c(e_j) = e_j^2 \quad j = 1, 2, 3 \quad \text{and} \quad c(e_i) = \frac{e_i^2}{2} \quad i = 4, \ldots, 10. \]

In benchmark period, all ten airlines are examined. To reflect heterogeneity on model parameters, quantities and profits are analysed in two different years, 2012 and 2014. In such way, 2013 data are solely considered for clustering companies. Year 2012 is the first time period in which EU-ETS started, potentially, with no abatement effort measures evaluated and/or introduced. To ensure market composition through the years, and comparability in terms of demand elasticity, without loss of generality, 2012 airline verified emissions are considered as a proxy for the benchmark period. Therefore, the proposed model predicts the following Cournot output and profit:

\[ q_{a,b} = \frac{a}{b} \quad \text{and} \quad \pi_{a,b} = \frac{a^2}{121 \cdot b} \quad \forall \quad i = 1, \ldots, 10. \]

The amount \( Q_b \) is assumed to be equal to 3,449,656 tonnes of verified emissions\(^{11} \) while two years later, under EU-ETS, in 2014 \( Q_b \) decreases to 2,117,003 tonnes. The cap is set to be \( \gamma = 0.95 \), the mean market price for the selected year is 5.96 Euros per tonne of \( \text{CO}_2 \), the percentage of allowances bought on the secondary market is \( \delta_m = 0.3615 \), and no allowances have been auctioned by the selected Italian companies (\( \delta_s = 0 \)), hence:

\[ \pi_{a,b,1} = \frac{(a - 7.71)^2}{121 \cdot b} + \frac{2.05}{10} \quad \text{with } i = 1 \quad \text{and} \quad \pi_{a,b,2} = \frac{(a - 0.55)^2}{121 \cdot b} + \frac{2.05}{10} \quad \forall \quad j = 2, \ldots, 10 \]

and \( Q_{E,1} = \frac{1}{11 \cdot b} (a - 7.71) \) and \( Q_{E,2} = \frac{7}{11 \cdot b} (a - 0.55). \)
\(^{12} \) This application suggests that EU-ETS profits in the two different airline groups are greater than in the benchmark period if and only if \( a_1 < 1.608 \cdot 3.85 \), and \( a_2 < 22.5 \cdot 0.2752. \)

The empirical simulation offers valuable insights on the role of the firms’ heterogeneity, as well as demand elasticity, in understanding the effect of EU-ETS on airlines’ profits. By mixing theoretical modelling and data-mining techniques (via cluster analysis), profit trends could be estimated, given abatement effort strategies of different airline categories and changes in \( \text{CO}_2 \) emission allowance prices.

\(^{11} \)\( Q_b = 3,449,656, \) \( \frac{3}{11} \) can be approximately equal to 3,794,621.

\(^{12} \)In 2014, Alitalia verified emissions were 1,578,058, Air Dolomiti 75,593, Siro 11,769 and all the seven remaining operators counted for 451,583 emissions. The intercept of the demand for first and second group, i.e. \( a_1 \) and \( a_2 \), can be approximated respectively to \( a_1 = 18.319,620 \cdot 7.71 \), and \( a_2 = 4,967,413 \cdot 0.55. \)
4. Conclusions

Based on an original microeconomic model, this paper explores the effects of applying the European emission trading scheme specifically to the aviation industry, and it offers an evaluation of its impact on Italian carriers. By explicitly allowing for abatement efforts and emission reduction incentives in the airline cost function, the results contribute to better understand the overall EU-ETS effects, thus, supporting policy-making decisions. Two main factors influence airline profits, when the EU-ETS is enforced: the share of allowances distributed free of charge ($\gamma$), and the airlines abatement effort cost ($\beta$).

Referring to $\gamma$, profits are positively influenced by the quantity of free allowances received. This is quite intuitive, as the more free of charge allowances are distributed to airlines, the less they are induced to buy permits on the market to cover their actual emissions if they suffer a deficit of allowances. Referring to $\beta$, its value depends on the abatement effort, that is, any kind of investment specifically targeted to reduce pollutant emissions. Consequently, whenever it takes a positive value, airlines shall incur into higher operational costs, and might experience lower profits. The latter point is crucial, because it contributes to explain the role of the provided EU-ETS incentives. The effect of penalising airlines is the same for all considered market structures, but to a greater extent, for those whose competitive forces are stronger.

Nevertheless, it is worth noting that, even if one could expect lower profits due to greater abatement efforts, overall effect remains uncertain, in relation to the magnitude of $\gamma$. From an industrial policy point of view, interactions among airline strategies to reduce GHG emissions, and their decisions on allowances allocated for free play an important role in reinforcing airlines innovation incentives. Formally, the larger the quota of permits granted for free, the lower $\gamma$, depressing its positive contribution to airline profits.

As explained, the effect of $\gamma$ and $\beta$ is also related to the value of $\Delta$, taking into account several factors: individual airlines strategies about total amount of sold and/or bought allowances, either on the secondary market or via auction; number of permits that firms decide to sell and/or buy in each market; level of allowances prices; intensity of sanctions. In particular, outcomes are strongly related to airlines strategies in response to the emissions trading scheme design. From a managerial perspective, airline abatement effort strategies might consider policy-maker decision to progressively increase the process of allowances auctioning.

From a different perspective, a negative effect on equilibrium outputs is registered. It depends merely on the relationship between unitary abatement effort costs, and airline strategies, but not on the share of free allowances individually assigned. In conclusion, observed variations of equilibrium quantities reflect new operational opportunities, for the carriers involved, and potentially open new markets, as well as the airline abatement effort cost encouraged with the EU-ETS.

Collusive outcome exhibits different levels of equilibrium quantities and profits with respect to oligopoly structure. Enhancing main differences are not referred to components discussed so far ($\beta, \gamma, \Delta$), still entering both in quantity and profit functions at the same manner: they relate only to EU-ETS exogenous factors, such as the number of firms on the market and the demand elasticity.

As for the role of CO2 emission allowance price ($P_b$), if the carbon price rises the abatement effort increases proportionally to compensate such variation effects. The price dynamics of CO2 emission allowances could encourage higher airline efficiency level, but it also affects airlines profits, although less than proportionally. For a given price, airlines profits increase linearly, according to the variation of the share of free of charge allowances. As CO2 emission allowance prices rise, profits increase exponentially, especially under collusion and deviation assumptions.

Finally, the proposed empirical application to Italy based airlines highlights the role of firms’ heterogeneity, as well as of demand elasticity in market equilibria. Demand estimation for the aviation sector ($a$), demand elasticity (proportional to $b$), and assumptions on model parameters ($a$, $b$) are crucial in determining airline profits under EU-ETS ($E$) period, compared to benchmark one ($B$).

This analysis also raises some challenging issues on the model construction, due to difficulties to properly capture aviation sector complexity. The lack of data on quantities supplied by airlines on each single operated route limits the capability to characterise market forces under competition, thus asking for relaxing the assumptions in the model to accomplish dynamic analyses.

Further research might be addressed to assess alternative designs of the EU-ETS scheme in terms of incentives, allowances and sanctions, compare the effects on competitiveness, efficiency level, profits and abatement efforts. Moreover, further research using dynamic modelisation should be carried on reaching a deeper understanding of industrial policy implications, following progressive changes in emission caps, and in the share of free allowances. Such an extension, enriched by optimizing routes perspective, seems a promising base for further research to improve characterisation of EU-ETS goals, in fighting global warming for the next few decades.

Appendix A. Proposition proofs

In this appendix, proofs of Propositions 1 and 2 are sketched out both for the homogeneous and the heterogeneous cases.

**Proposition 1.** In the Cournot-Nash equilibrium for the benchmark period ($B$), the payoff for the $i$th airline company is equal to

$$
\pi_{i,B} = \frac{1}{(n+1)^b} (a-\alpha)^2 \quad \forall \quad i = 1,\ldots,n.
$$

**Proof.** The maximization of Eq. (2) determines reaction curves for airline operators. In particular, denoting the quantity offered by the other companies with $q_{i-B} = \sum_{\neq i} q_j$, the reaction curve $\forall \quad i = 1,\ldots,n$, equals to

$$
R_{i,B}(q_{i,B}) = \frac{1}{2b} (a-bq_{i-B} - \alpha - \beta \alpha_i)^2
$$

inducing a Cournot-Nash equilibrium output
\[ q_i^n = \frac{1}{(n + 1)b} \left[ a - \alpha - \beta \left( n e_i^n - \sum_{j \neq i} e_j^n \right) \right] \quad \forall \ i = 1,...,n. \]  

(10)

Simply, the total quantity sold on the market is

\[ Q = \sum_{i=1}^{n} q_{i,E} = \frac{1}{(n + 1)b} \left[ n a - n \alpha - \beta \sum_{i=1}^{n} \left( n e_i^n - \sum_{j \neq i} e_j^n \right) \right]. \]  

(11)

The optimal efficiency level for this Cournot-Nash equilibrium before the EU-ETS is such that there are no explicit incentives for companies to invest in environment-friendly solutions, meaning that \( e_{i,E} \approx \ldots = e_{n,E} = 0 \). As a consequence, the output reduces to

\[ q_{i,E} = \frac{1}{(n + 1)b} (a - \alpha) \quad \forall \ i = 1,...,n \quad \text{and} \quad Q_B = \sum_{i=1}^{n} q_{i,E} = \frac{n}{(n + 1)b} (a - \alpha). \]  

(12)

On adding the optimal solutions into the profit function, the payoff equals to

\[ \pi_{i,E} = \frac{1}{(n + 1)^2b} (a - \alpha)^2 \quad \forall \ i = 1,...,n \]  

(13)

is obtained. \( \square \)

**Proposition 2.** In the Cournot-Nash equilibrium for the EU-ETS period \((E)\), the payoff for the \( i \)-th airline company is equal to

\[ \pi_{i,E} = \frac{(a - \alpha - \frac{1}{2} \sqrt{2 \Delta^2 \beta^2})^2}{(n + 1)^2b} + \frac{\Delta Y}{n} \quad \forall \ i = 1,...,n; \quad \Delta = (R_{i,E} \delta_0 + P_{n,E} \delta_m + R_{i,E} \delta_l - P_{i,E} \delta_l) \]  

(14)

**Proof.** In the second period, the reaction curve for the \( i \)-th airline operator \((i = 1,...,n)\) given the maximization of Eq. (3) and reaction curves of all the other companies denoted by \( q_{i,E} = \sum_{k \neq i} q_{k,E} \) is

\[ R_{q_{i,E}} (q_{i,E}) = \frac{1}{2b} \left( a - bq_{i,E} - \alpha - \beta e_i^n - \Delta \right). \]  

(15)

Recalling that \( \Delta = \delta_n (P_{n,E} - P) \), the reaction curve is influenced by the EU-ETS through the rate of allowances purchased on the carbon market or the rate of allowances not surrendered to the European Commission. The Eq. (16) below describes the Cournot-Nash equilibrium output

\[ q_{i,E} = \frac{1}{(n + 1)b} \left[ a - \alpha - \beta \left( e_i^n - \sum_{j \neq i} e_j^n \right) - \Delta \left( n \frac{1}{e_{i,E}} - \sum_{j \neq i} \frac{1}{e_{j,E}} \right) \right] \quad \forall \ i = 1,...,n. \]  

(16)

In addition, given the first order condition (FOC) and the homogeneity assumption, the optimal efficiency effort or green investment induced by the EU-ETS to reduce emissions is \( e_{1,E} = \ldots = e_{n,E} = e_E = \frac{1}{\sqrt{2 \Delta}} \), which induces an output level equal to

\[ q_{i,E} = \frac{1}{(n + 1)b} \left[ a - \alpha - \frac{3}{2} \sqrt{2 \Delta^2 \beta} \right] \quad \forall \ i = 1,...,n \]  

(17)

with

\[ Q_E = \sum_{i=1}^{n} q_{i,E} = \frac{n}{(n + 1)b} \left( a - \alpha - \frac{3}{2} \sqrt{2 \Delta^2 \beta} \right). \]  

(18)

Finally, the payoff given the optimal Cournot output of the \( i \)-th company has value

\[ \pi_{i,E} = \frac{(a - \alpha - \frac{1}{2} \sqrt{2 \Delta^2 \beta})^2}{(n + 1)^2b} + \frac{\Delta Y}{n} \]  

(19)

Main results associated with the non-homogenous firm assumption are also derived. Reaction curves and associated optimal outputs in the benchmark period are respectively:

\[ R_{Q_{i,E}} (q_{i,E}) = \frac{1}{2b} \left( a - bq_{i,E} - \alpha e_i^n \right); \quad q_{i,B} = \frac{1}{(n + 1)b} \left( a - \alpha - \frac{1}{k} \left( (1 - k) \delta_k - \delta_l \right) \right) \quad \forall \ i = 1,...,kn \]  

\[ q_{j,E} = \frac{a - \alpha - \frac{kn}{(n + 1)b} (a - \alpha)}{(n + 1)b} \quad \forall \ j = 1,...,(1-k)n. \]  

Moreover, reaction curves and associated optimal outputs in the ETS period are respectively:

\[ R_{Q_{i,E}} (q_{i,E}) = \frac{1}{2b} \left( a - bq_{i,E} - \alpha \frac{3}{2} \sqrt{2 \Delta^2 \beta} \right) \]
Appendix B. Monopoly

Proposition 3. The monopoly output for the aviation sector before and after the introduction of the ETS induces, respectively, profit levels

\[ \pi_{i,B} = \frac{(a-\alpha)^2}{4nb} \quad \text{and} \quad \pi_{i,E} = \frac{(a-\alpha-\frac{1}{2}\sqrt{2\Delta k})^2}{4nb} + \frac{\Delta \gamma}{n} \quad \forall \ i = 1,...,n. \]  

(20)

Proof. Under the assumption of a cartel (i.e. a monopoly), the maximization problem in the benchmark and in the EU-ETS period is, respectively

\[ \max_{q_i=1,...,n} \pi_{i,B} = \max_{q_i=1,...,n} \sum_{i=1}^{n} \left[(a-b) \sum_{i=1}^{n} q_iB - q_iB^\alpha + e_iB q_iB^\beta \right] \]  

and

\[ \max_{q_i=1,...,n} \pi_{i,E} = \max_{q_i=1,...,n} \sum_{i=1}^{n} \left[(a-b) \sum_{i=1}^{n} q_iE - q_iE^\alpha + e_iE q_iE^\beta \right]. \]  

(21)

(22)

Deriving first order conditions, optimal efficiency levels reach the already identified amounts, i.e. \( e_{i,B} = 0 \) and \( e_{i,E} = \frac{\Delta \gamma}{2b} \). Moreover, the optimal monopoly output is, for every \( i = 1,...,n \), in the two distinct period equal:

\[ q_{i,B} = \frac{a-\alpha}{2nb} \quad \text{and} \quad q_{i,E} = \frac{1}{2nb} \left(a-\alpha-\frac{3}{2}\sqrt{2\Delta k} \right). \]  

(23)

Then, the total industry outputs are

\[ Q_B = \sum_{i=1}^{n} q_{i,B} = \frac{(a-\alpha)^2}{nb} \quad \text{and} \quad Q_E = \frac{1}{2nb} \left(a-\alpha-\frac{3}{2}\sqrt{2\Delta k} \right) \]  

and profits associated with the two distinct cases are:

\[ \pi_{i,B} = \frac{(a-\alpha)^2}{4nb} \quad \text{and} \quad \pi_{i,E} = \frac{(a-\alpha-\frac{1}{2}\sqrt{2\Delta k})^2}{4nb} + \frac{\Delta \gamma}{n} \quad \forall \ i = 1,...,n. \]  

(24)

Appendix C. Collusion

Proposition 4. If \( n-1 \) firms agree on collusion, but the \( j \) th deviates, then profit functions are, in the benchmark case

\[ \pi_{i,B} = \frac{(n+1)(a-\alpha)^2}{8bn^2} \quad \text{and} \quad \pi_{j,B} = \frac{(n+1)(a-\alpha)^2}{16bn^2} \]  

and in the EU-ETS period

\[ \pi_{i,E} = \frac{(n+1) \left(a-\alpha-\frac{1}{2}\sqrt{2\Delta k} \right)^2}{8bn^2} + \frac{\Delta \gamma}{n} \quad \text{and} \quad \pi_{j,E} = \frac{(n+1) \left(a-\alpha-\frac{1}{2}\sqrt{2\Delta k} \right)^2}{16bn^2} + \frac{\Delta \gamma}{n}. \]  

Proof. The results illustrated in this proposition can be easily derived from first order conditions. Note that the optimal output for the \( j \)th firm that does not collude in the two periods are, respectively

\[ q_{j,B,D} = \frac{(n+1)(a-\alpha)}{4nb} \quad \text{and} \quad q_{j,E,D} = \frac{(n+1) \left(a-\alpha-\frac{1}{2}\sqrt{2\Delta k} \right)}{4nb} \]  

such that the quantity produced by the industry in the benchmark and ETS periods will be

\[ Q_B = q_{j,D} + \frac{(n-1)}{2nb} (a-\alpha) \quad \text{and} \quad Q_E = q_{j,E,D} + \frac{(n-1) \left(a-\alpha-\frac{3}{2}\sqrt{2\Delta k} \right)}{2nb} \].
Finally, given optimal outputs, profits for the \( n-1 \) firms that collude are equal to

\[
\pi_{i,E} = \frac{(n+1)(a-\alpha)^2}{8bn^2} \quad \text{and} \quad \pi_{j,E} = \frac{(n+1)(a-\alpha-\frac{1}{2}\sqrt{2\Delta^2\beta})^2}{8bn^2}
\]

and profits for the \( j \)th that deviates are equal to

\[
\pi_{j,b} = \frac{(n+1)(a-\alpha)^2}{16bn^2} + \gamma\Delta \quad \text{and} \quad \pi_{j,E} = \frac{(n+1)(a-\alpha-\frac{1}{2}\sqrt{2\Delta^2\beta})^2}{16bn^2} + \gamma\Delta.
\]

**Appendix D. Simulations**

**Figs. 3–6**

**Fig. 3.** Modelling the effects of CO\(_2\) emission allowances price \((P_m)\) on main parameters under the Cournot oligopoly. Note: both simulations are respectively based on the following assumptions: \( \delta_n = 0; \gamma = 0.85; a = \alpha = b = 1; \beta = 2; n = 10; P = 18 \) and \( \delta_n = 0; \gamma = 0.85; a = \alpha = b = \beta = 1; n = 10; P = 1.2P_m \). Source: own elaboration.

**Fig. 4.** Modelling the effects of CO\(_2\) emission allowances price \((P_m)\) on profits under Cournot oligopoly, collusion and deviation. Note: both simulations are respectively based on the following assumptions: \( \delta_n = 0; \gamma = 0.85; a = \alpha = b = 1; \beta = 2; n = 10; P = 18 \) and \( \delta_n = 0; \gamma = 0.85; a = \alpha = b = \beta = 1; n = 10; P = 1.2P_m \). Source: own elaboration.
Fig. 5. Modelling the effects of the share of allowances free of charge $\gamma$ on profits under Cournot oligopoly, collusion and deviation. Note: both simulations are respectively based on the following assumptions: $\pi_E = 7$; $\delta_0 = 0$; $\alpha = \alpha = b = \beta = 1$; $n = 10$; $P_e = 1.2P_m$.

Source: own elaboration.

Fig. 6. Modelling the effects of CO$_2$ emission allowances price ($P_m$) on profits under Cournot oligopoly with and without homogeneous firms. Note: both simulations are respectively based on the following assumptions: $P = 1.2P_m$; $\delta_0 = 0$; $\gamma = 0.85$; $\alpha = \alpha = b = \beta = 1$; $n = 10$ and, respectively, $k = 0.5$ and $k = 0.8$ for the heterogenous cases. Homogenous cases are derived considering simply $k = 0$ and $k = 1$ respectively.

Source: own elaboration.

References


