Game-theoretic Economic Models of Duopolies Applied to Green ICT Design

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***Abstract*—Green design of ICT is fundamental to obtain sustainable global development of advanced applications. Its implementation is influenced by many economic factors, including the choices of both operators and consumers, as well as government incentives. In this paper, we study this problem under a game theoretic perspective based on classic competition models, namely Bertrand and Cournot duopolies, with proper modification to capture the traits of green ICT conversion. We explore how market equilibria and public subsidies determine whether competing enterprises put into action green practices. Due to its generality, our proposed framework can be adapted to practical evaluations in specific contexts of local economies.**

***Index Terms*—Game Theory; Green design; Industrial economics.**

I. Introduction

Information and communication technology (ICT) service providers operate in a market characterized by a fierce competition, where the strategies to grow revenues and more in general the business models are open to speculation [1]. It is generally agreed that the customers of such a market are highly dynamic and can switch to a competing operator much more frequently than other services [2]–[4]. This principle is independently verified by many studies about different countries [5]–[7], confirming that the choice of and loyalty to an ICT service depend on the level of satisfaction and the alternatives advertised by competitors in terms of service quality and tariffs, but also brand image, while other factors such as the individual income of the customer or the subscription duration are less impactful [8], [9].

The technological novelty offered by ICT solutions such as the Internet of things (IoT) and fifth generation (5G) telecommunication systems, which pervade everyday activities [10], can be a true benchmark for the providers, to consolidate and expand their customer platforms. This is also true in light of the new trend arising in recent years of eco-sustainability of our planet increasingly in stress because of misuse of natural resources. Several forecasts predict that the global carbon budget is not lasting until 2050, unless the usage of technology and its (undoubtedly beneficial in itself) opening to a wider share of the world population is rethought [11]. The scientific community has reached an almost-unanimous consensus about the causal connection of climate change and human activities, which in the last century and a half have caused a worrisome global warming due to greenhouse gases [12]. A key role in this context is played by ICT: about 1% of worldwide energy consumptions is due to mobile telecommunication providers, and a similar amount relates to user devices [13], [14].

For these compelling reasons, green design principles for ICT are put in place, so as to obtain eco-friendly design of operations also exploiting renewable energies, which determines several technical challenges [15]–[20]. At the same time, more and more governments are sponsoring green ICT, and the awareness of consumers for sustainability is on the rise. For example, this has become a serious concern in Italy, where the 2020 report of the 6th National Sustainability Observatory [21] indicates that more than 70% of the population is interested or passionate about the subject and motivated to evolve their behavior in their consuming choices. This is in line with more general findings for other countries (see, e.g., [8], [22], [23]): despite the differences in focus and methodologies, there is a general consensus that green design in ICTs may be beneficial for both the eco-social cause itself, as well as for the brand reputation. As a result, more and more companies choose to address this increasing consumer awareness: according to the biennial report of the Global Sustainable Investment Alliance (GSIA) [24], worldwide investments for green design are growing by 34% every 2 years.

We analyze the market for green ICT to assess its strategic milieu for sustainable eco-friendly operation, accounting for the role of the customers, the government incentives, and the added value created by green design [25]. Generally, competition models are analyzed from the perspective of game theory, and ICT service provision is no exception [26], [27].

In particular, we start from the classic models of Bertrand and Cournot's [28]. We present an extension for their possible application to green ICT and we apply it to a duopoly scenario where competing providers make a preliminary strategic decision of investing into green design, which is more expensive but might benefit from an increased appeal from the consumers, as well as incentives from the government. We derive the resulting Nash equilibria and we compare the different approaches, ultimately arguing how they can be used as a prediction instruments to drive the choices of operators and regulatory bodies to promote green ICT design.

The remainder of this paper is organized as follows. In Section II we introduce the models implemented and the game

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dynamics. In Sections III and IV we apply the Bertrand and Cournot models, respectively, to the specific economic context under examination. In Section V we elaborate the comparison between the models. Section VI concludes the paper.

II. Economic Competition and Game Dynamics

Consider a competition of two ICT operators, active in the same country/region, which can choose whether to adopt a green design or a traditional one. These choices are denoted with I (i.e., to implement green design) and N (not to implement any green choice). This decision is made preliminarily and independently by each operator; in game theory jargon, this is referred to as a "simultaneous" move, even though it does not need to happen at the exact same time, it suffices that the operators do not collude or consult with each other, but choose as the result of a true competition [29].

There may be government incentives for the operators to adopt green practices, whose extent is common knowledge among the operators [25]. Also, after the preliminary decision made by the operators, we assume that the consumers adhere to either of them and contribute to the revenue of the chosen operator, according to standard duopoly models (namely, Bertrand and Cournot duopolies) taken from game theory and their resulting Nash equilibria [28]. The fact that the competition takes place on such a market economy, and the revenues are ultimately determined by a free choice of the customers, depending on these duopoly models, is also common knowledge among the operators. Being rational players, the operators can anticipate the choices of the customers and make their preliminary decision accordingly [27].

Finally, to make the model more interesting, we introduce a further element about the customer type. In practice, every consumer can be of the "green" or "non-green" type, with respective probabilities p and $1-p$. This further parameter tunes the preference of the consumers towards operators adopting green practices. The exchange coefficient varies according to a function f defined as

$$f(p) = 1.3 - 0.6p\,. \tag{1}$$

In this way, each operator choosing strategy I gains reputation over the green customers and aim at better revenues from them. If $p > 0.5$, the exchange toward green goods is favored by the majority of the customers, as $f(p) > 1$, whereas if $p < 0.5$, the majority of the customers are not promoting green design. The value of p is also known to the operators. The implementation details will be further explained in Sections III and IV for the Bertrand and Cournot duopolies, respectively.

III. Bertrand Duopoly

Bertrand competition model [28] describes an industry structure in which firms compete on the prices of the products. We adopt the Bertrand model with imperfect substitutes, described by the following equation

$$\pi_i = (a - s_i + b\,s_j)(s_i - c)$$

where π_i is operator i's profit, s_i is the price set by operator i, c is the operation cost, b is the exchange rate between operators, and a is the initial market potential.

We can refine the concept of imperfect substitutes by using an exchange rate that is function of p, specifically $b = f(p)$ as defined in (1). In addition, we include other two parameters to match the economic context under investigation: (i) an additional production cost g when converting to green design, and (ii) a term $\mathtt{i}$ quantifying the incentives given by the government to support green design.

This leads to a normal form of the game where the expected payoffs for each game outcome are as follows, depending on the strategic choices of the operators, denoted by a pair xy with $x, y \in \{I, N\}$ being the preliminary actions selected by the two operators. The outcome of the duopoly model as the result of the operators' strategic choices is written in the following for all the four cases.

$$II : \begin{cases} \pi_1^{II} = \mathtt{i} \\ \\ \pi_2^{II} = \mathtt{i} \end{cases}$$

$$IN : \begin{cases} \pi_1^{IN} = \big(s_1 - (c+g)\big)\big(a - f(p)s_1 + s_2\big) + \mathtt{i} \\ \\ \pi_2^{IN} = (s_2 - c)\big(a - s_2 + f(p)s_1\big) \\ \end{cases}$$

$$NI : \begin{cases} \pi_1^{NI} = (s_1 - c)\big(a - s_1 + f(p)s_2\big) \\ \\ \pi_2^{NI} = \big(s_2 - (c+g)\big)\big(a - f(p)s_2 + s_1\big) + \mathtt{i} \\ \end{cases}$$

$$NN : \begin{cases} \pi_1^{NN} = 0 \\ \\ \pi_2^{NN} = 0 \end{cases}$$

We can compute the resulting prices s_1 and s_2 (for the two operators, respectively), by looking for local maxima, i.e., a best response to the other player's choice, obtaining the following solutions.

$$II : \quad s_1^* = s_2^* = c + g$$

$$IN : \begin{cases} s_1^* = \frac{3a+c}{3f(p)} + \frac{2}{3}(c+g) \\ \\ s_2^* = a + \frac{2}{3}(c) + \frac{1}{3}(c+g)f(p) \end{cases}$$

$$NI : \begin{cases} s_1^* = a + \frac{2}{3}(c) + \frac{1}{3}(c+g)f(p) \\ \\ s_2^* = \frac{3a+c}{3f(p)} + \frac{2}{3}(c+g) \end{cases}$$

$$NN : \quad s_1^* = s_2^* = c$$

In particular, in the cases II and NN, i.e., whenever the operators adopt a similar approach to green design, the model becomes a classical Bertrand duopoly. Accordingly, the

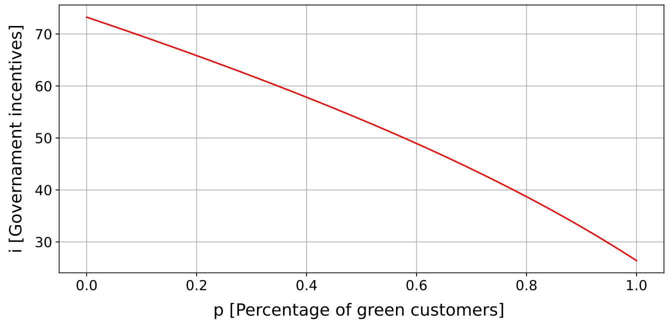

Fig. 1: Government incentive $\mathtt{i}$as function of p to get mixed strategy $m(0.7, 0.3)$

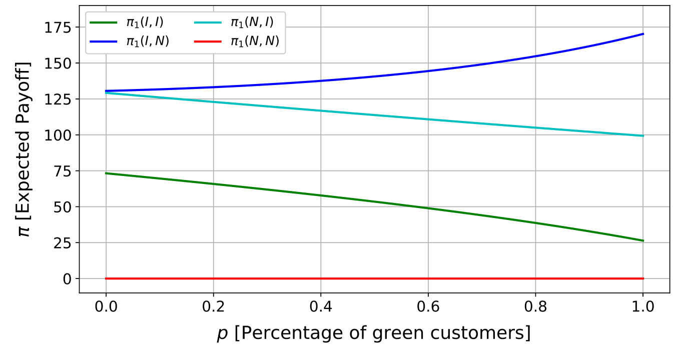

Fig. 2: Payoff of Operator 1 as a function of p in the mixed strategy NE $m = (0.7, 0.3)$

customers choose the cheaper price, so the operators in turn lower the price until they reach a Nash Equilibrium at the same price $s_1^* = s_2^*$, also equal to the production cost, which is $c + g$ or c, for II and NN, respectively.

From now on, to simplify the discussion, we set some parameters as a=10, c=5, g=2, as well as $f(p)$ being according to (1), while we allow for tunable government incentives $\mathtt{i}$ and the prior probability p of customer type.

We are going to look for the minimum amount of public incentives that forces the operators to adopt a mixed strategy where green design is chosen 70% of the time. This is in line with the general findings of green interests in the public opinion [21]–[23] but can clearly be changed to any value. This goal can be formalized imposing a mixed strategy in which the strategies I and N are played with probabilities equal to $\alpha = 0.7$ and $1 - \alpha$, respectively. The context is symmetric and thus we can find α through the *indifference theorem* [28] by imposing

$$u_1(I, \alpha) = u_1(N, \alpha)$$

$$\text{where: } \begin{cases} u_1(I, \alpha) = \alpha \cdot \pi_1^{II} + (1 - \alpha) \cdot \pi_1^{IN} \\ u_1(N, \alpha) = \alpha \cdot \pi_1^{NI} + (1 - \alpha) \cdot \pi_1^{NN} \end{cases}$$

For $\alpha = 0.7$ we compute the function that describes how the incentives must vary as a function of p::

$$\Rightarrow \mathtt{i} = \frac{-55.64p^3 + 984.21p^2 - 6114.9p + 6434.8}{87.86 - 40.55p}$$

The relation between $\mathtt{i}$ and p is plotted in Fig. 1. Remarkably, to obtain a rate $\alpha = 0.7$ of green operation, the government must provide incentives to the operators even when 100% of customers are sensitive to green design.

On the other hand, if we set no incentives and only rely to a green awareness of the consumers quantified in $p = 0.72$, as is the case for Italy [24], imposing as above $u_1(I, \alpha) = u_1(N, \alpha)$ results in

$$\begin{cases} \mathtt{i} = 0 \\ p = 0.72 \\ u_1(I, \alpha) = (1 - \alpha) \cdot \pi_1^{IN} \\ u_1(N, \alpha) = \alpha \cdot \pi_1^{NI} \end{cases}$$

$$\Rightarrow \alpha = 0.4995$$

Thus, according to the model, one should expect around half of the ICT operators in Italy to follow green design policies just by virtue of natural choices of the customers. In Fig. 2, we can observe how the payoff of one operator vary as a function of the customer type probability p.

From Fig. 2, we get a surprising trend when both operators invest in green design, since their revenues decrease as the percentage of the population attentive to green products increases. However, remembering that in case II the model is a classic Bertrand and therefore the only equilibrium is for s_1^*=s_2^*=c+g, the final payoff comes from government incentives $\mathtt{i}$. As p increases, the required $\mathtt{i}$ decreases since the entire operation of both operators follows green design principles. Thus, according to this model, it is more likely to observe the operators choosing contrasting strategies, i.e., IN or NI. In particular, we see that for $p = 0$ the two strategies are equivalent, while, as p increases, the operator choosing I gets a higher revenue, which is in line with the added value of green design. Finally, if all the customers are eco-friendly (i.e., $p \to 1$), (I, I) Pareto dominates (N, N), but the best choice for the operators is, again, to aim at different markets, i.e., polarizing on choices such as (I, N) or (N, I).

Should the government decide to impose green design for all the operators, the incentives should be high enough to make I a strictly dominant strategy. Furthermore, to prevent that the two operators agree in a cartel over repeated interactions, so that neither actually adopts green design, we must impose that (I, I) Pareto Dominates (N, N). These restrictions lead to the following system to be solved:

$$\begin{cases} u_1(I, I) > u_1(N, I) \\ u_1(I, N) > u_1(N, N) \\ u_1(I, I) > u_1(N, N) \end{cases}$$

where the first two inequalities imply that I strictly dominates N and the last one means that (I, I) is Pareto efficient. The system above implies

$$\mathtt{i} \geq \max(1.96(p^2 - 16.2p + 65.9), \frac{49(36p^2 + 444p + 1369)}{90(6p - 13)}, 0)$$

Specifically, Pareto Efficiency of (I, I) is always verified. This was already visible from Fig. 1 where the incentives to achieve green design 70% of the times were shown. Clearly, incentives $\mathtt{i}$ must increase even more for this share to be raised to 100%.

For a final overview, in Fig. 3 we can see the trend in case I is the best strategy to play. In particular, we show how the government incentives must vary to ensure that strategy I is dominant, according to the percentage p of consumers who prefer green products and the additional cost g that conversion to green production entails for the operator. We have imposed an additional cost g that varies between 0 and 5, where 5 corresponds to the doubling of the initial cost c.

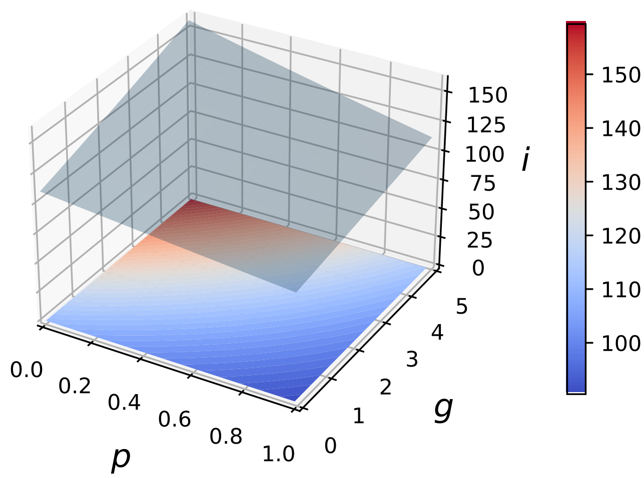

Fig. 3: Recommended value of $\mathtt{i}$ according to the Bertrand model versus p and g.

From the graph, we can see that if there are no consumers oriented to the purchase of green products ($p = 0$), the government needs to increase the incentives to compensate the additional costs for the providers to offer green operation. This trend is valid for any value of p, so the incentives that the government must provide are directly proportional to the additional cost g. If we now observe the trend of the incentives as a function of p, as expected, they decrease as p increases. This is because the more customers are inclined to buy green goods, the more the company is pushed to produce them, consequently the state can provide fewer incentives to ensure that the best strategy played by the operators is still I. Therefore the trend of $\mathtt{i}$ is inversely proportional to p. Putting everything together, we see that the incentives that the state must provide in the case of the model under consideration are minimal when $p = 1$ and $g = 0$, however, also in this case $\mathtt{i} > 0$, so in order for investing in green to be the best strategy, the state must intervene even if the whole population is green-aware and the additional cost for the operators is zero.

IV. Cournot Duopoly

Cournot duopoly model [28] describes a market structure in which agents compete on the amount of provision. The model is described by

$$\pi_i = q_i(a - q_i - q_j - c)$$

where π_i is the profit of operator i, q_i is its operation volume, c is the sustained cost for one unit of operation volume, and a is a term describing the market potential.

The extended duopoly framework presented in Section II, with an additional cost g for green action, and an incentive $\mathtt{i}$ from the government, leads to the following payoffs:

$$II : \begin{cases} \pi_1^{II} = q_1\big(a - q_1 - q_2 - (c+g)\big) + \mathtt{i} \\ \pi_2^{II} = q_2\big(a - q_1 - q_2 - (c+g)\big) + \mathtt{i} \end{cases}$$

$$IN : \begin{cases} \pi_1^{IN} = q_1\big(a - f(p)q_1 - g(p)q_2 - (c+g)\big) + \mathtt{i} \\ \pi_2^{IN} = q_2\big(a - f(p)q_1 - g(p)q_2 - c\big) \end{cases}$$

$$NI : \begin{cases} \pi_1^{NI} = q_1\big(a - g(p)q_1 - f(p)q_2 - c\big) \\ \pi_2^{NI} = q_2\big(a - g(p)q_1 - f(p)q_2 - (c+g)\big) + \mathtt{i} \end{cases}$$

$$NN : \begin{cases} \pi_1^{NN} = q_1(a - q_1 - q_2 - c) \\ \pi_2^{NN} = q_2(a - q_1 - q_2 - c) \end{cases}$$

At this point, we can compute the values of q_1 and q_2 at the NEs by deriving the best responses, which leads to the following results.

$$NN : \quad q_1^* = q_2^* = \frac{a-c}{3}$$

$$IN : \begin{cases} q_1^* = \frac{(2g+c-a)(60p+70)}{3(36p^2-36p-91)} \\ q_2^* = \frac{10(g+a-c)}{3(6p+7)} \end{cases}$$

$$NI : \begin{cases} q_1^* = \frac{10(g+a-c)}{3(6p+7)} \\ q_2^* = \frac{(2g+c-a)(60p+70)}{3(36p^2-36p-91)} \end{cases}$$

$$II : \quad q_1^* = q_2^* = \frac{a-(c+g)}{3}$$

From now on, we set the parameters $a = 20$ and $c = 5$, while we investigate the variations of p, $\mathtt{i}$, and g.

To be consistent with Bertrand's model, we look for the minimum amount of government incentives that forces the operators to adopt green policies at least 70% of the times. The procedure is similar, and the results are shown in Fig. 4, where we fixed $g = 1$, and in Fig. 6 where we let vary also the production costs. Analytically, $\mathtt{i}$ is found as

$$\mathtt{i} \geq \max\left(0, \frac{-10p^4 + 75p^3 + 93p^2 - 111p + 135}{1.2p^4 - 2.5p^3 - 5.2p^2 + 6.5p + 8.2}\right)$$

Fig. 5 shows the payoff π_1 of Operator 1, for the four different cases of pure strategies (the two operators choosing either I or N with probability 1). The same counterintuitive result previously found for the Bertrand duopoly is shown,

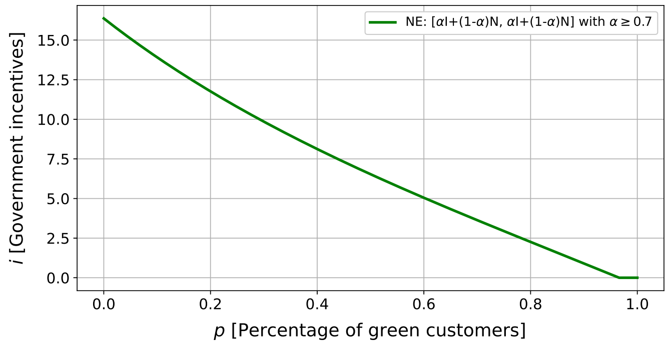

Fig. 4: Government incentive i as function of p to get mixed strategy $m(0.7, 0.3)$

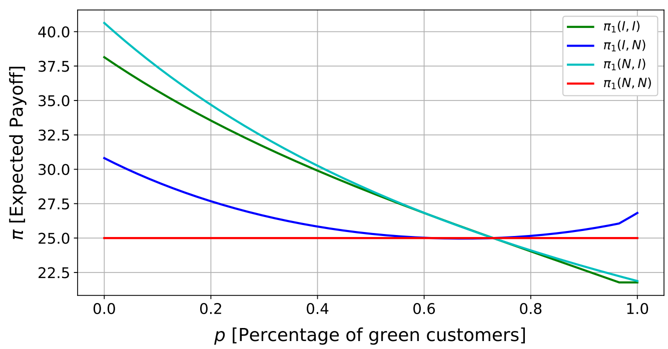

Fig. 5: Payoffs of Operator 1 as a function of p and g in the mixed strategy NE $m = (0.7, 0.3)$

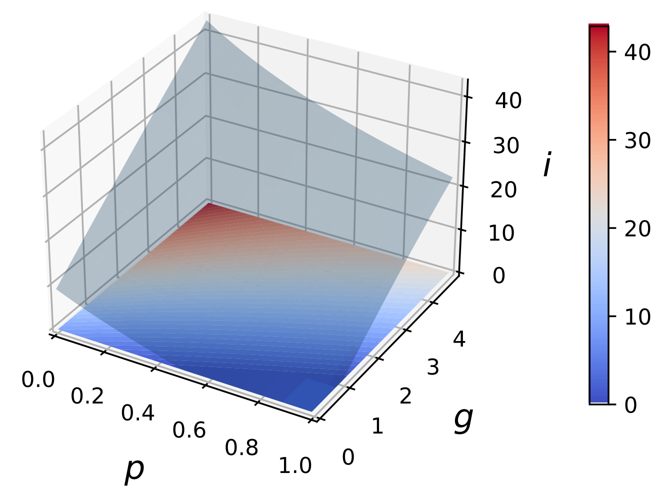

Fig. 6: Government incentive i as a function of p and g in the mixed strategy NE $m = (0.7, 0.3)$

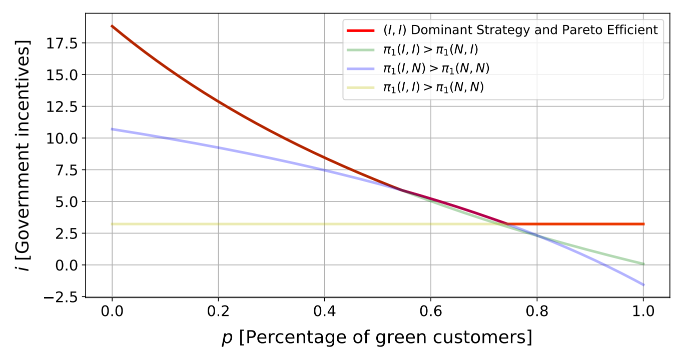

Fig. 7: Government incentive i as function of p to have I as a dominant strategy and (I, I) as Pareto Efficient outcome.

that is, when p increases (more customers are driven toward eco-friendly design), the payoffs of the operators in the II case decrease. This is due to the fact that the additional production cost g remains constant but the government subsidies i decrease because they are not needed anymore to impose that at least the 70% of the firms production would be green. Notably, even when all the customers prefer green design (i.e., $p = 1$), the (N, N) outcome Pareto dominates the (I, I) one, and the best choice for the firms is to aim at different markets, i.e., to polarize on either the (I, N) or (N, I) outcomes.

Similar to what done in Section III, we want to analyze, also within the Cournot duopoly, the required incentives by the government to ensure that both operators adopt a sustainable design. In game theory formalism, this means that I must be a strictly dominant strategy. Furthermore, in order to prevent that the two providers agree in a cartel that never adopts green operation, we must impose that (I, I) Pareto dominates (N, N). These constraints lead to the following conditions

$$\begin{cases} u_1(I, I) > u_1(N, I) \\ u_1(I, N) > u_1(N, N) \\ u_1(I, I) > u_1(N, N) \end{cases}$$

thus resulting in a system of equations that can be promptly solved by numerical methods. The procedure is entirely analogous to what shown before for the Bertrand's model and is omitted here for brevity. Fig. 7 shows the resulting value of government subsides i that meets the requirements.

Once again, we remark that without imposing (I, I) to be Pareto Efficient, we could face a collusion in a dynamic setup, where the operators agree to never invest in green design. Thus, such a condition is not strictly needed but serves for the model to be realistic in the long run.

V. Bertrand-Cournot Comparison

The two models make use of slightly different parameters and therefore cannot be precisely juxtaposed. Yet, they are similar in the broad sense of comparing how the operators adapt their strategies depending on the government incentives and the customers type probability.

The main difference is the profit that operators can obtain when both decide to not adopt any green design (NN): in the Bertrand model, the payoff is 0 for both operators, instead in the Cournot model joint strategy NN can also become Pareto efficient under certain market conditions. For the other cases, the duopoly models are quite similar. Whenever either operator chooses a green strategy, the profit of the other (see Operator 1's profit when the joint choice is II or NI) decreases when the share p of green customers increases. When the considered operator is instead the only one with green design (as is the case for Operator 1 when the game unfolds as IN), the results are different: in the Bertrand duopoly, the profit increases with p, while in the Cournot duopoly it decreases at first, until reaching the payoff of NN; then, once a certain threshold of p is exceeded, it begins to increase.

Finally, the analysis of the mixed strategy NE $m{=}(0.7, 0.3)$, the trend of incentive `i` as a function of p is decreasing for both models, in particular being concave in the case of the Bertrand duopoly and convex in the Cournot duopoly.

VI. Conclusions

General economic models that faithfully represent the actual market are hard to derive. However, it is important to get the gist of what expected in the evolution of ICTs, due to their involvement with an ever increasing share of the world population and their ability to affect other markets and everybody's life as a result [10].

In this paper, we proposed an adaptation of some classic models, namely Bertrand and Cournot duopolies, to make them suitable for the analysis of green design for ICT operation. We studied how the models behave in a roughly similar economic context, where we consider government incentives and a variable share of the consumers as attentive to green design. We remarked the similarities and differences of the two models in characterizing the market competition. Furthermore, we computed the incentives required from an external authority (in our case, the government) to support the operators towards an environmentally sustainable transition.

We argued about possible collusions among operators to avoid green design and how to prevent them. It would be useful to consider a specific analysis, possibly involving a multistage game with the addition of a discount factor and the antitrust authority modeled as an explicit player, in order to add further realism to the problem. Another idea for future studies would be to expand the attitude of ICT consumers toward green design in a more detailed distribution than a single variable, through the instrument of Bayesian games [19], [29].

Our model also seeks for a good compromise between complexity and practicality. While firmly grounded in classic models, some assumptions are necessarily speculative. A final extension, which we plan to carry out in future work, is an experimental validation of the trends to confirm their realism.

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