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Fair international protocols for the abatement of GHG emissions*

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Abstract

We study the design of fair international protocols for the abatement of GHG emissions. We formulate normative principles, pertaining to countries' population, emission history, and (business as usual) future emissions, as axioms for allocation rules. We show that combinations of these axioms characterize the so-called *equal per capita allocation rules*, with or without historical accountability. The allocations provided by these rules are in stark contrast with the allocation suggested by the Kyoto protocol, which is close to the allocation in proportion to the current and business-as-usual emissions, suggested by the *equal per emission* (*grandfathering*) rule. As we illustrate, equal per capita allocations admit more emissions to developing countries with large populations. And, with historical accountability, developed countries with large historical emissions are clearly penalized.

JEL numbers: *D63, Q52, Q54.*
Keywords: climate change; GHG reduction targets; allocation rules; historical accountability; history independence; equal per capita allocation

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1 Introduction

Sharing responsibility for the global commons has long been (and will remain) a growing concern in the globalized world economy. Since 1920, there have been more than 140 international environmental agreements to confront global environmental externalities, many of which constituted successful multinational efforts to protect globally valued ecosystems and to control certain damaging emissions (e.g., Libecap, 2014). For instance, in 1987, and in response to a dramatic seasonal depletion of the ozone layer over Antarctica, the international society forged a landmark treaty, the so-called *Montreal Protocol*, which successfully called for drastic reductions in the global production, consumption, and emissions of ozone-depleting substances (e.g., Velders et al., 2007). It was followed by stronger reduction agreements in both developed and developing regions; complete elimination in developed countries by the year 2000 and in developing countries by the year 2010.

Somewhat surprisingly, this is in contrast with a pressing issue for the last decades: the control on the anthropogenic release of greenhouse gas (GHG) emissions, which largely contribute to what, by now, is already considered a *climate emergency*.

As early as 1979, scientists from 50 nations met at the First World Climate Conference and already agreed that alarming trends for climate change made it urgently necessary to act (e.g., Ripple et al., 2019). In 1997, 39 countries (representing about two thirds of global emissions in 1990) signed the Kyoto Protocol, which promised to reduce their emissions of 6 GHGs by 5.2%, compared with 1990 levels, by 2008-2012 (e.g., Eyckmans and Hagem, 2011). These signatories were allocated an initial amount of emission permits corresponding to their quantitative emissions limits. The Protocol did not impose binding emission targets on the remaining (developing countries) signatories. To facilitate cooperation among the countries, the protocol offered mechanisms such as the *International Emission Trading*, the *Joint Implementation* and *Clean Development Mechanisms* through which the countries could achieve their targets jointly or separately (e.g., Maamoun, 2019). Although the US did not ratify it, the Kyoto Protocol came into force in 2005. It was, nevertheless, terminated in 2012. Four years later, the so-called Paris Agreement was signed. Unlike its predecessor, the Paris Agreement allows for voluntary and nationally determined targets. The specific climate goals are thus politically encouraged, rather than legally bound. In that same year, the European Commission presented a new burden-sharing framework, called the *Effort Sharing Decision*, and proposed several new features of the European framework aimed at limiting GHG emissions (e.g., Babonneau et al., 2018). A year later, US President Donald Trump announced his intention to withdraw the US from the agreement.

Much has been written about the reasons why there have been no successful sustained multilateral controls on the abatement of GHG emissions. For instance, Ambec and Coria (2013, 2018) argue that the spillover effect of local pollution abatement on GHG emissions might be negative or induce perverse incentives. But it is frequently argued that, in international negotiations, the equity and justice concerns in allocating responsibilities for emissions' reduction plays a crucial role (e.g., Okereke and Dooley, 2010; Alcaraz et al., 2018; Zhu et al., 2018; Jabbar et al., 2019). In the earliest key step towards an international agreement on the issue of global climate change, the United Nations Framework Convention on Climate Change (UNFCCC) already stated the importance of equity and differentiated responsibilities among countries:

> "The Parties should protect the climate system for the benefit of present and future generations of human kind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."(United Nations 1992, Principle 1 in Article 3)

Concrete formulations of equity and "differential responsibilities" have been widely debated in the literature (see, for instance, Ju and Moreno-Ternero (2017) and the references cited therein). Our main objective here is to provide a novel perspective in this debate through investigating the matter using the axiomatic approach, a prominent approach within the economic literature on fair allocation (e.g., Thomson, 2011).

Most of the earlier normative investigations on international protocols for the abatement of GHG emissions propose ethical principles directly in terms of allocation rules. Two well-known rules in this literature, promoted mainly by scholars siding with developing countries, are equal per capita allocation rules, with or without historical accountability (e.g., Grübler and Fujii, 1991; Smith, 1991; Grubb, 1995; Neumayer, 2000; Bou-Habib, 2019). We provide foundations for the two rules by identifying, in our formal model of fair allocation of reduction targets, basic normative principles that implicate the two rules.

Regional communities, or countries, constituting the global society have, in general, different populations, different pollution histories and different future pollution paths (in business as usual). How should these differential characteristics be taken into account in allocating the burden of reducing current and future emissions, or allocating reduction targets? We address this issue upon considering a stylized model of fair allocation and formulating well-known normative principles, pertaining to emission history or population, as axioms for allocation rules.

Our axiom of *historical accountability* holds each community fully accountable for historical emissions, whereas the polar axiom of *history independence* requires the opposite, dismissing historical emissions. Our population axiom requires that individuals in different communities should be given equal rights as long as their communities have identical historical, current and future emissions in per capita terms.

Our main results establish normative foundations of equal per capita allocation rules with or without historical accountability. More precisely, *historical accountability* together with our population norm, and other standard axioms in the fair allocation literature, characterizes the *equal per capita rule with historical accountability*. Replacing *historical accountability* with *history independence* in this result, we characterize the *equal per capita rule* (without historical accountability).

We then compare the rules, so characterized, with other fair allocation rules. Special emphasis is made on the comparison with the allocation suggested by the Kyoto protocol (KP). Such an allocation is close to the allocation in proportion to the current and business-as-usual emissions, obtained from the so-called *equal per emission* (*grandfathering*) rule. The main difference is that equal per capita allocations (with or without historical accountability) admit more emissions to developing countries with large populations than the KP allocation. Furthermore, the equal per capita allocation with historical accountability penalizes developed countries with a history of large emissions, allocating them emission reduction responsibilities instead of emission allowances.

The rest of the paper is organized as follows. We present our model, axioms and rules in Section 2. We collect all of our results in Section 3. We provide empirical applications in Section 4. We conclude in Section 5. We defer some proofs and the most technical aspects of our analysis to the Appendix.

2 The Model

Consider a global society N of n communities that share a common resource (the global commons). Each community $i \in N$ is populated by ν_i members (in the past, now, and in the future).[1] It has emitted and will emit pollutants damaging the commons. If all communities do their business as usual, the damage is expected to be so disastrous that they agreed to restrict the pollution damage in the future to a certain aggregate amount. How should this agreed target be shared across communities?

Each community $i \in N$ is characterized by the amount of historical (up to the present) emission h_i, and the amount of its current and future emission c_i when the community is under business as usual. We refer to c_i as the BAU emission of community i. Throughout the paper, we assume that $c_i > 0$, for each $i \in N$. Let $h \equiv (h_i)_{i \in N}$, $c \equiv (c_i)_{i \in N}$ and $\nu \equiv (\nu_i)_{i \in N}$. The amount of damage to the global commons is determined by the total historical emission $\bar{h} \equiv \sum_{i \in N} h_i$ and the total current and future emissions $\bar{c} \equiv \sum_{i \in N} c_i$. The historical, the current, and the future emissions are perfect substitutes in producing the damage, which is measured by their sum. Hence, when all communities are under business as usual, the damage is given by $\bar{h} + \bar{c}$. When this damage $\bar{h} + \bar{c}$ is larger than the target E, the communities should reduce their BAU emissions to meet the target and the total reduction should equal $\bar{h} + \bar{c} - E$. In other words, the global society is allowed to emit up to the level $E - \bar{h}$ in the future. We consider the problem of allocating this amount of allowable emission $E - \bar{h}$ to the communities, denoted by $P \equiv (h, c, \nu, E)$.[2] Let $\mathcal{P} \equiv \{(h, c, \nu, E) \in \mathbb{R}^{3n+1}_+ :$ for all $i \in N$, $c_i > 0$, and $\bar{h} + \bar{c} \geq E\}$ be the set of all these problems.

An *allocation* $x \equiv (x_i)_{i \in N} \in \mathbb{R}^N$ for $P \equiv (h, c, \nu, E)$ is a profile of individual permits $x_i \in \mathbb{R}$ for each $i \in N$ satisfying the target; that is,

$$\bar{x} = \sum_{i \in N} x_i = E - \sum_{i \in N} h_i = E - \bar{h}.$$

At allocation x, each community i needs to reduce its future emissions by the amount of $c_i - x_i$. A community $i \in N$ may be allocated a negative

[1] We assume that the population distribution is fixed across communities for the sake of simplicity and rule out the issue of differentiated rates of population growth across regions.

[2] Although we are allocating the amount of allowable emission $E - \bar{h}$, we do not denote a problem as $(c, \nu, E - \bar{h})$ because some of the axioms we formalize later require more information regarding historical emissions than just its aggregate value. Furthermore, $E - \bar{h}$ could be negative, which would require to change the domain of our problems.

amount $x_i < 0$, which means that community $i \in N$ needs to reduce not only its whole BAU emission c_i but also face an additional reduction of $|x_i|$ (*e.g.*, emission reduction in other communities through providing either technological support, or natural resources, or purchasing their permits, etc.). An *allocation rule* $f : \mathcal{P} \to \mathbb{R}^N$ associates with each problem $(h, c, \nu, E) \in \mathcal{P}$ an allocation $x \in \mathbb{R}^N$ for P.

Allocation Rules

We now present two rules, which are the main focus of our analysis. They are well known in the debate on international allocation of GHG emissions rights, as well as in the literature on fair allocation. The two are egalitarian rules providing equal rights to every human being in all communities, in the current and future generations. They differ from each other in dealing with past emissions; one fully disregarding historical emissions and the other holding current and future generations fully accountable for historical emissions.

The first rule allocates the total allowable emissions on an equal per capita basis.[3] Every present and future member of the global society should receive equal emission rights independently of which community it belongs to and how much its community has emitted in the past. Thus, such an allocation to each community is in proportion to its population. Formally,

Equal per capita rule, f^{EPC}: For each $(h, c, \nu, E) \in \mathcal{P}$ and each $i \in N$,

$$f_i^{EPC}(h, c, \nu, E) = \frac{\nu_i}{\bar{\nu}}(E - \bar{h}),$$

where $\bar{\nu} \equiv \sum_{i \in N} \nu_i$. Note that this rule does not take into account historical emissions.

The next rule modifies the equal per capita rule augmenting it with differential responsibilities across countries, depending on their historical emissions. Each community i with the historical emission h_i/ν_i above the historical mean $\bar{h}/\bar{\nu}$ in per capita terms has the so-called *historical emission debt*, $h_i/\nu_i - \bar{h}/\bar{\nu}$, and their debt should be discounted from their equal per capita shares.[4] Likewise, equal per capital shares of the other communities j with

[3]The same allocation rule or its variants have been proposed by several authors; see the extensive survey by Gardiner (2004, pp.583-589). In particular, Singer (2002, pp.35-43) proposed equal per capita allocation on the basis of fairness.

[4]The idea of natural debt has been pioneered by Grübler and Fujii (1991) and Smith (1991). See also Grubb (1995) and Neumayer (2000).

historical emissions below the historical mean should be augmented by their "historical credit or immunities", $\bar{h}/\bar{\nu} - h_j/\nu_j$.[5] Formally,

Historical equal per capita rule, f^{HEPC}: For each $(h, c, \nu, E) \in \mathcal{P}$ and each $i \in N$,

$$f_i^{HEPC}(h, c, \nu, E) = \frac{\nu_i}{\bar{\nu}}\left(E - \bar{h}\right) + \nu_i\left(\frac{\bar{h}}{\bar{\nu}} - \frac{h_i}{\nu_i}\right).$$

This rule was proposed by Neumayer (2000) in a more complex setting as the *rule with historical accountability*.[6]

Instead of allocating on an equal per capita basis, one might consider doing so on an equal per (BAU) emissions basis. Formally,

Equal per emission rule, f^{EPE}: For each $(h, c, \nu, E) \in \mathcal{P}$ and each $i \in N$,

$$f_i^{EPE}(h, c, \nu, E) = \frac{c_i}{\bar{c}}\left(E - \bar{h}\right).$$

The previous rule can be modified through augmenting it with historical credit or immunities "per BAU emissions". The global historical emission per BAU emissions is given by $\bar{h}/\bar{c}$ and community i's historical emission per BAU emission is given by h_i/c_i. Hence the historical credit per BAU emission of community i is given by the difference $\bar{h}/\bar{c} - h_i/c_i$. Thus,

Historical equal per emission rule, f^{HEPE}: For each $(h, c, \nu, E) \in \mathcal{P}$ and each $i \in N$,

$$f_i^{HEPE}(h, c, \nu, E) = \frac{c_i}{\bar{c}}(E - \bar{h}) + c_i\left(\frac{\bar{h}}{\bar{c}} - \frac{h_i}{c_i}\right).$$

Axioms

We now formulate the main normative principles we consider for rules. The first two axioms postulate two opposite viewpoints concerning how to handle historical emissions.

[5] This general principle of comparing individual performance with average performance to determine allocations is frequently obtained in the literature on resource allocation. A recent instance appears in Bergantiños and Moreno-Ternero (2020).

[6] Neumayer (2000) considers a setting with more past and future years and with varying population over generations.

We say that community i is free from historical responsibility when its historical emission equals zero. Hence i's emission allowance $f_i((0, h_{-i}), c, E)$ is the amount it deserves when it has no historical responsibility, other things being equal to $P \equiv (h, c, \nu, E)$. Our first axiom requires that each community i should give up its historical emission fully out of this amount it deserves free from historical responsibility; this way, each community should take the full historical responsibility.

Historical Accountability. For each $(h, c, \nu, E) \in \mathcal{P}$ and each $i \in N$,

$$f_i(h, c, \nu, E) = f_i((0, h_{-i}), c, \nu, E) - h_i.$$

The axiom of *historical accountability* says that the allocation to community i is determined by first assessing the amount i deserves when it has no guilt (historical emissions), other things being equal, and then subtracting from it its historical emission.[7]

Contrary to *historical accountability*, the next axiom requires that historical emissions should be disregarded in the allocation of current and future emission permits. This idea may gain some support if people in the past were ignorant of harmful effects of their emissions and their descendants now and in the future have no comparative advantage from their historical emissions (or, elsewhere, all benefits from the historical emissions are evenly distributed across the current and the future population in the global society).

History Independence. For each $(h, c, \nu, E) \in \mathcal{P}$ and each $(h', c', \nu', E') \in \mathcal{P}$, if $E - \bar{h} = E' - \bar{h}'$ and $(c, \nu) = (c', \nu')$, then

$$f(h, c, \nu, E) = f(h', c', \nu', E').$$

We also consider several axioms that are variants of similar well-known axioms in the literature of fair allocation.

The next axiom is an extension of the standard equal treatment property, which models the principle of impartiality, with a long tradition in the theory of justice (e.g., Moreno-Ternero and Roemer, 2006). In our model, members of any two countries with equal per capita historical emissions and equal per capita current emissions can be regarded as having equal moral rights. The

[7] This axiom is reminiscent to the so-called partial-implementation invariance axiom, recently introduced by Thomson (2017, 2019) for the problem of adjudicating conflicting claims.

next axiom says that these two countries should then be treated equally in per capita terms.

Equal Treatment of Per-Capita-Equals. For each $(h, c, \nu, E) \in \mathcal{P}$ and each pair $i, j \in N$, if $h_i/\nu_i = h_j/\nu_j$ and $c_i/\nu_i = c_j/\nu_j$, then

$$f_i(h, c, \nu, E)/\nu_i = f_j(h, c, \nu, E)/\nu_j.$$

Some communities may have excessively large BAU emissions that cannot be satisfied by the available total amount of emissions. The next axiom requires that such excessive emissions should not make any difference in allocating permits.[8]

Irrelevance of Excessive Per-Capita Emissions. For each $(h, c, \nu, E) \in \mathcal{P}$, each $i \in N$ and each $c_i' > 0$, if $c_i/\nu_i \geq E - \bar{h}$ and $c_i'/\nu_i \geq E - \bar{h}$, then

$$f(h, c, \nu, E) = f(h, (c_i', c_{-i}), \nu, E).$$

We also consider a pair of axioms reflecting meaningful (and basic) lower and upper bounds. Lower and upper bounds have a long tradition of use within normative economics and, in particular, frequent instances occur within the literature on fair allocation (e.g., Thomson, 2011; 2019).

First, a standard axiom reflecting a cap (upper bound) on allocations. More precisely, the axiom states that no country can receive an amount higher than its BAU emission.

Claim Upper Bound. For each $(h, c, \nu, E) \in \mathcal{P}$, each $i \in N$,

$$f_i(h, c, \nu, E) \leq c_i.$$

The counterpart lower bound is naturally formalized resorting to historical emissions. More precisely, the axiom states that no country can receive a negative overall amount, when added to the historical emission.

History Lower Bound. For each $(h, c, \nu, E) \in \mathcal{P}$, each $i \in N$,

$$f_i(h, c, \nu, E) + h_i \geq 0.$$

[8]This axiom is similar to *truncation invariance* in claims problems, which states that claiming beyond the dividend is irrelevant. In that setting, *truncation invariance* is a weakening (e.g., Stovall, 2014) of the famous axiom of contraction independence, originally used by Nash (1950) in the domain of bargaining problems, in what happened to be one of the first applications of the axiomatic approach. In the context of individual choice, a similar axiom is sometimes known as Sen's condition (Sen, 1969).

The last axiom requires that the allocation should be additive in resources.[9] Note that, in our problem, given historical emissions h and emission target E, the total amount to be allocated is determined by $E - \bar{h}$. The amount to be divided under $(h + h', E + E')$ equals the sum of the amount to be divided under (h, E) and the amount to be divided under (h', E'). The next axiom requires that the allocation under $(h + h', E + E')$ should equal the addition of the two allocations under (h, E) and under (h', E').

Resource Additivity. For each $j = 1, 2, 3$, such that $(h^j, c^j, \nu^j, E^j) \in \mathcal{P}$, $(c^j, \nu^j) = (c, \nu)$, $h^1 = h^2 + h^3$, and $E^1 = E^2 + E^3$,

$$f(h^1, c, \nu, E^1) = f(h^2, c, \nu, E^2) + f(h^3, c, \nu, E^3).$$

In Table 1, we summarize the behavior of the rules introduced above with respect to the axioms we consider.

Axioms\Rules	*HEPC*	*EPC*	*HEPE*	*EPE*
Historical Accountability	$\mathrm{Y}^{(1)}$	N	$\mathrm{Y}^{(3)}$	N
History Independence	N	$\mathrm{Y}^{(2)}$	N	$\mathrm{Y}^{(4)}$
Equal Treatment of per-capita Equals	$\mathrm{Y}^{(1)}$	$\mathrm{Y}^{(2)}$	N	N
Irrelevance of Excessive per-capita Emissions	Y	$\mathrm{Y}^{(2)}$	N	N
Claim Upper Bound	N	N	$\mathrm{Y}^{(3)}$	$\mathrm{Y}^{(4)}$
History Lower Bound	$\mathrm{Y}^{(1)}$	N	$\mathrm{Y}^{(3)}$	N
Resource Additivity	$\mathrm{Y}^{(1)}$	$\mathrm{Y}^{(2)}$	$\mathrm{Y}^{(3)}$	$\mathrm{Y}^{(4)}$

Table 1: Axioms and Rules. 'Y' ('N', respectively) in each cell means that the column rule satisfies (does not satisfy) the row axiom. For each k =1, 2, 3, and 4, $\mathrm{Y}^{(k)}$ means the row axiom is used in Theorem k that characterizes the column rule.

3 Results

As we show in this section, our main results are characterizations of the historical equal per capita rule and the equal per capita rule. Both results

[9]This notion has a long tradition of use in axiomatic work (e.g., Shapley, 1953; Debreu, 1960).

use *equal treatment of per-capita-equals*, *irrelevance of excessive emissions* and *resource additivity*. Now, among the many rules satisfying these three axioms, we show that *historical accountability* or *history independence* pin down the two rules.

More precisely, our first result provides a characterization of the *historical equal per capita rule* based on *historical accountability*, *equal treatment of per-capita-equals*, *irrelevance of excessive per-capita emissions*, and *resource additivity*.

Theorem 1. *A rule satisfies historical accountability, equal treatment of per-capita-equals, irrelevance of excessive per-capita emissions, and resource additivity if and only if it is historical equal per capita rule.*

Proof. It is straightforward to show that the *historical equal per capita rule* satisfies the four axioms in the statement. Conversely, let f be an allocation rule satisfying the four axioms. Let $(h, c, \nu, E) \in \mathcal{P}$ and $i \in N$. By *resource additivity*,

$$f(h, c, \nu, E) = f(\mathbf{0}_n, c, \nu, E) + f(h, c, \nu, 0).^{10} \tag{1}$$

Let M be a natural number such that $E/M \leq \min\{c_j/\nu_j : j \in N\}$. Let $E' \equiv E/M$ and $c' \equiv (\nu_j E')_{j\in N}$. Note that all current emissions are excessive at $(\mathbf{0}_n, c', \nu, E')$. Then, by *irrelevance of excessive per-capita emissions*, $f(\mathbf{0}_n, c, \nu, E') = f(\mathbf{0}_n, c', \nu, E')$. By *equal treatment of per-capita-equals*, $f(\mathbf{0}_n, c', \nu, E') = (\nu_j E'/\bar{\nu})_{j\in N}$. Therefore,

$$f(\mathbf{0}_n, c, \nu, E') = \left(\frac{\nu_j}{\bar{\nu}} E'\right)_{j\in N}.$$

As f satisfies *resource additivity* and $E = M \cdot E'$,

$$f(\mathbf{0}_n, c, \nu, E) = \left(\frac{\nu_j}{\bar{\nu}} E\right)_{j\in N}. \tag{2}$$

Lemma 5 in the appendix shows $f(h, c, \nu, 0) = -h$, which, together with (1) and (2), implies that for each $i \in N$,

$$f_i(h, c, \nu, E) = \frac{\nu_i}{\bar{\nu}} E - h_i.$$

□

[10] By $\mathbf{0}_n$ we refer to the vector in the n-dimensional space in which all coordinates are zero.

As stated in the next result, replacing *historical accountability* in Theorem 1 by *history independence*, we obtain a characterization of the *equal per capita rule*.

Theorem 2. *A rule satisfies history independence, equal treatment of per-capita-equals, irrelevance of excessive per-capita emissions, and resource additivity if and only if it is the equal per capita rule.*

Proof. It is straightforward to show that the *equal per capita rule* satisfies the four axioms in the statement. Conversely, let f be an allocation rule satisfying the four axioms. Let $P \equiv (h, c, \nu, E) \in \mathcal{P}$. We distinguish two cases:

Case 1. $E - \bar{h} \geq 0$. Let $P' \equiv (\mathbf{0}_n, c, \nu, E - \bar{h})$. By *history independence*, $f(P) = f(P')$. Let M be a natural number such that $(E - \bar{h})/M \leq \min\{c_i/\nu_i \colon i \in N\}$. Let $\hat{E} \equiv (E - \bar{h})/M$ and $\hat{c} \equiv (\nu_i \hat{E})_{i\in N}$. By *irrelevance of excessive per-capita emissions*, $f(\mathbf{0}_n, c, \nu, \hat{E}) = f(\mathbf{0}_n, \hat{c}, \nu, \hat{E})$. Note that per capita current emissions are the same among all communities with $\hat{c}$, $\hat{E}$ and the original population ν. Hence, by *equal treatment of per-capita-equals*, $f(\mathbf{0}_n, c, \nu, \hat{E}) = f(\mathbf{0}_n, \hat{c}, \nu, \hat{E}) = (\nu_i \hat{E}/\bar{\nu})_{i\in N}$. By *resource additivity*, $f(P') = (\frac{\nu_i}{\bar{\nu}}(E - \bar{h}))_{i\in N}$, which, together with $f(P) = f(P')$, implies that

$$f_i(h, c, \nu, E) = \frac{\nu_i}{\bar{\nu}}(E - \bar{h}),$$

for each $i \in N$.

Case 2. $E - \bar{h} < 0$. Let c'' be such that for each $i \in N$, $c''_i = \nu_i \lambda$ with $\lambda > 0$, and $h'' \equiv (\nu_1 \bar{h}/\bar{\nu}, \ldots, \nu_n \bar{h}/\bar{\nu})$. Let $P'' \equiv (h'', c'', \nu, E)$. By *irrelevance of excessive per capita emissions*, $f(P) = f(h, c'', \nu, E)$, and, by *history independence*, $f(h, c'', \nu, E) = f(P'')$. Hence $f(P) = f(P'')$. Now, by *equal treatment of per-capita-equals*, $f(P'') = (\frac{\nu_i}{\bar{\nu}}(E - \bar{h}))_{i\in N}$, which, together with $f(P) = f(P'')$, implies that

$$f_i(h, c, \nu, E) = \frac{\nu_i}{\bar{\nu}}(E - \bar{h}),$$

for each $i \in N$.

□

We also characterize the equal per emission rules. To do so, as stated in the next results, we only need to replace the pair of axioms made of *equal treatment of per-capita-equals* and *irrelevance of excessive per-capita emissions* by the bounds axioms. More precisely,

Theorem 3. *A rule satisfies historical accountability, claim upper bound, history lower bound and resource additivity if and only if it is the historical equal per emissions rule.*

Proof. It is straightforward to show that the *historical equal per emissions rule* satisfies the four axioms in the statement. Conversely, let f be an allocation rule satisfying the four axioms. Let $(h, c, \nu, E) \in \mathcal{P}$ and $i \in N$. By *resource additivity*,

$$f(h, c, \nu, E) = f(\mathbf{0}_n, c, \nu, E) + f(h, c, \nu, 0).$$

By *claim upper bound*,

$$f(\mathbf{0}_n, c, \nu, \bar{c}) = c.$$

Thus, by *resource additivity*,

$$f(\mathbf{0}_n, c, \nu, E) = \left(\frac{c_j}{\bar{c}}E\right)_{j \in N}.$$

Now, by *history lower bound*,

$$f(h, c, \nu, 0) = -h.$$

Thus,

$$f_i(h, c, \nu, E) = \frac{c_i}{\bar{c}}E - h_i,$$

for each $i \in N$. □

In the case of the *equal per emissions rule*, one simply needs to replace in Theorem 3 *historical accountability* and *history lower bound* by *history independence.*

Theorem 4. *A rule satisfies history independence, claim upper bound, and resource additivity if and only if it is the equal per emissions rule.*

Proof. It is straightforward to show that the *equal per emissions rule* satisfies the three axioms in the statement. Conversely, let f be an allocation rule satisfying the three axioms. Let $P \equiv (h, c, \nu, E) \in \mathcal{P}$. We distinguish two cases:

Case 1. $E - \bar{h} \geq 0$. Let $P' \equiv (\mathbf{0}_n, c, \nu, E - \bar{h})$. By *history independence*, $f(P) = f(P')$. Now, by *claim upper bound*, $f(\mathbf{0}_n, c, \nu, \bar{c}) = c$. Thus, by *resource additivity*, $f(\mathbf{0}_n, c, \nu, E - \bar{h}) = (\frac{c_i}{\bar{c}}(E - \bar{h}))_{i \in N}$, which, together with $f(P) = f(P')$, implies that

$$f_i(h, c, \nu, E) = \frac{c_i}{\bar{c}}(E - \bar{h}),$$

for each $i \in N$.

Case 2. $E - \bar{h} < 0$. Let $h'' = (\bar{h} - E)/n, \ldots, (\bar{h} - E)/n)$ and $P'' \equiv (h'', c, \nu, 0)$. By *history independence*, $f(P) = f(P'')$. By *resource additivity*, $f(P'') = f(h'', c, \nu, E'') - f(0, c, \nu, E'')$, for each $E'' > 0$. If we assume $E'' \geq \bar{h} - E$, and apply Case 1, it follows that

$$f_i(P'') = \frac{c_i}{\bar{c}}(E'' - \bar{h''}) - \frac{c_i}{\bar{c}}E'' = \frac{c_i}{\bar{c}}(E - \bar{h}),$$

for each $i \in N$. Thus,

$$f_i(h, c, \nu, E) = \frac{c_i}{\bar{c}}(E - \bar{h}),$$

for each $i \in N$. $\square$

4 Application

We provide in this section numerical applications. More precisely, we derive CO_2 emissions permits allocated by our two main allocation rules and compare them with other allocations, with a special emphasis on the one obtained from the Kyoto protocol (KP).

4.1 Regional and country-wise allocation of the total emission target

The countries are categorized into four groups defined by the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC): OECD countries as in year 1990 (OECD90), Asia (ASIA), Africa and Latin America (ALM), and countries undergoing economic changes (REF). We use the so-called SRES A1FI Emissions Scenarios for the claims of each group.[11] The claims are defined as the remainder of

[11]The key assumptions are *"A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying*

the projected cumulative emissions in year 2050: REF = 300.36; ALM = 618.78; OECD90 = 768.47; ASIA = 1,048.57. For historical emissions and populations, we use the CAIT of the World Resources Institute.[12]

The three target emissions for 2000-2050 are taken from Meinshausen et al. (2009). In particular, we consider 1,440, 1,000, and 745 $GtCO_2$ that correspond to 50%, 25%, and 0% of exceeding 2°C increase in global temperature relative to pre-industrial levels, respectively.

		EPC	*HEPC*	*EPE*	*HEPE*
Budget	REF	261.20	237.60	158.08	66.19
1,440 Gt	ALM	214.25	300.50	325.65	485.67
CO_2	OECD90	202.77	-256.80	404.43	78.40
(50 %)	ASIA	761.78	1158.70	551.84	809.74
Budget	REF	181.39	157.79	109.77	17.89
1,000 Gt	ALM	148.78	235.03	226.15	386.17
CO_2	OECD90	140.81	-318.75	280.85	-45.18
(25%)	ASIA	529.01	925.93	383.22	641.12
Budget	REF	135.13	111.54	81.78	-10.10
745 Gt	ALM	110.84	197.09	168.48	328.50
CO_2	OECD90	104.91	-354.66	209.24	-116.80
(0 %)	ASIA	394.12	791.03	285.50	543.40

Table 1: Allocation of CO_2 emission allowances for regions

Table 1 provides the allocations that our four rules, EPC, HEPC, EPE and HEPE, yield for the four regions. Both EPC and HEPC allocate emission permits in proportion to population. Hence they allocate relatively more

themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality". See `https://www.ipcc-data.org/sim/gcm_clim/SRES_TAR/ddc_sres_emissions.html`. Accessed on December 30, 2019.

[12]Climate Analysis Indicators Tool (CAIT) is a six-gas, multi-sector, and internationally comparable data set for 186 countries. It also includes the UNFCCC Annex I country-reported greenhouse gas emissions.

amounts to the regions with larger populations such as ASIA, REF, ALM, which is in contrast with how the other rules allocate. In particular, both EPC and HEPC allocate the lowest amount to OECD90 as this region has the smallest population. In the case of HEPC, due to the highest historical emission and the smallest population in OECD90, this region is strongly penalized. On the other hand, the allocation to ASIA under HEPC is much higher than under any other rule since this region is distinguished by its large population and low historical emission.

Both EPE and HEPE allocate emission permits in proportion to current and future BAU emissions. Hence EPE allocates more to OECD90 and ASIA than to the other regions, and HEPE allocates much more to OECD90 than HEPC does. Nevertheless, due to the penalty incurred by historical accountability, HEPE allocates a substantially smaller amount to OECD90 than EPE.

		EPC	*HEPC*	*EPE*	*HEPE*
	France	6.92	-13.51	6.96	-13.41
	Germany	8.61	-54.46	15.47	-38.82
	Italy	6.32	-1.06	8.17	3.17
Budget	Spain	4.89	2.93	5.53	4.39
745 Gt	UK	6.72	-48.41	9.86	-41.25
CO_2	Canada	3.69	-12.57	9.79	1.35
(0 %)	US	33.18	-216.60	105.79	-51.04
	Japan	13.35	-4.35	21.96	15.28
	(South) Korea	5.27	5.57	21.67	42.96
	China	142.32	259.31	160.33	300.36
	India	134.16	287.92	44.64	83.83

Table 2: Allocation of CO_2 emission allowances for countries

Table 2 reports the allocations by the four rules to 11 European, American and Asian countries, assuming the target emission amount 745 GtCO_2. Among them are 9 current OECD member countries and 2 developing countries, China and India. The same comparison can be made among the four rules as is made using regional allocations in Table 1. The two developing countries with massive populations (China and India) are treated quite differently under EPE and HEPE, due to the difference in their (current and future) BAU emission. EPE allocates much larger amount to China than to India, as China has much larger BAU emission than India. The two countries are treated similarly under EPC and HEPC as they are similar in terms of population and historical emission, and these rules disregard their difference in BAU emission. Among developed countries, HEPC allocates larger amounts to Spain and Korea than the other 7 developed countries as these two countries have less historical emission. Likewise, comparing EPE and HEPE, the rate of penalty from historical accountability is lower for these two countries than the other 7 developed countries. In particular, HEPE allocates more to Korea than EPE does; this is in contrast with all the other 8 developed countries, which are penalized under HEPE due to historical accountability. All developed countries are treated more favorably under EPE (or HEPE) than under EPC (or HEPC respectively) and so are they, with the exception of Korea, under EPC (or EPE) than under HEPC (or HEPE respectively).

4.2 Comparison with the Kyoto Protocol allocation

In this section, we compare the allocation proposed by the Kyoto Protocol as the emission allowances in 2010 with the allocations by our four rules, EPC, HEPC, EPE and HEPE. The total emission allowance in 2010 is the sum of the emission allowances of Annex I countries and the actual emissions of non-Annex I countries under the Kyoto Protocol (KP, below). These amount to 15,334 million tons CO_2 and 27,675 million tons CO_2 respectively.[13] Since we deal with "annual" emission allowances in this comparison, we convert the historical emissions into the historical emissions per year, that is, the cumulative historical emissions (1855-1999) divided by the remaining 40 years (from the base year 2010) until the target year of zero emission, 2050. The set of countries is defined by the set of parties in the Kyoto Protocol, consisting of two categories, Annex I and non-Annex I. EU15 is the 15 EU countries in the Annex I group. We also consider the other countries in the Annex I group, among which are Australia, Canada, Japan, US, and also the EIT countries

[13]Emission allowances of Annex I countries are calculated by applying agreed reduction rates to the base year (1990) emission, available in UNFCCC (2002) and the Kyoto protocol. Emission allowances to non-annex I countries are their BAU emissions in 2010, avaiable in the data from SRES A1FI emissions scenarios.

in the region of Eastern Europe and the former Soviet Union. We treat all EIT countries as a single community (EIT in Table 3). We also treat all non-Annex I countries in Asia other than China, India and Korea as a single community. China, India and Korea have three representative characteristics in the non-Annex I group in terms of development history, current emission and population, which are the three key variables. Hence treating the three country cases separately is useful for drawing useful comparison of the four rules and the KP allocation in terms of their performances over countries with different characteristics.

		HEPC	*EPC*	*HEPE*	*EPE*	*KP*
Annual Emission Allowances	Australia	-32	140	506	486	532
in 2010 under the KP	Canada	-194	213	430	614	539
in million ton CO_2 units	(South) Korea	312	304	661	529	574
	Japan	328	771	1,165	1,309	1,063
	India	11,589	7,745	1,991	1,570	1,706
	EU15	-1,883	2,438	75	3,698	3,681
	US	-4,329	1,915	2,889	6,559	4,547
	EIT	-1,137	1,746	3,434	4,687	4,833
	China	11,141	8,216	10,692	7,928	8,615

Table 3: Allocation of the total annual CO_2 emission allowances in 2010 under the Kyoto Protocol

Among the four rules in Table 3, EPE allocation is closest to the KP allocation, as is evident in Figure 1. This is because of its *grandfathering* feature, rewarding the BAU emission levels. In particular, the US is allocated a relatively higher amount than in the KP allocation, rewarding its high level of BAU emission. The *grandfathering* feature allows China, which, together with US, is among the countries with the highest BAU emission, to receive much more allowances than India, despite their similarity in terms of population and emission history; similarly, HEPE treats China more favorably than India. EPC rewards countries with large population such as China and India despite their disparity in BAU emission. Under EPC, developed countries or regions with a small population receive much smaller allowances than under the KP or EPE allocations, as their BAU emissions are not taken into account. HEPC penalizes severely developed countries in Europe and North America with long and substantial emission history, resulting in negative emission allowances. This allows the developing countries with a history of low emission and with a large population such as China and India to receive much more emission allowances than under EPC. Japan and Korea, with relatively large BAU emissions per capita, are treated more favorably by the KP or EPE allocations than by the EPC or HEPC allocations. HEPC penalizes Japan more than Korea as Japan's historical emissions are higher than Korea's. Due to Korea's exceptionally fast economic growth, it has a history of relatively low emissions, which allows it to get more under HEPC (or HEPE) than under EPC (or EPE respectively).

5 Discussion

We have presented in this paper a stylized model for the problem of setting GHG reduction targets. We have formalized normative principles with wide appeal as axioms for allocations rules. Our main results provide characterization results for two focal rules (*equal per capita* and *historical equal per capita*) combining some of those axioms. One of our results (Theorem 1) can be seen as complementary with Neumayer's endorsement of historical accountability. Another of our results (Theorem 2) can be seen as providing rationale for the counterpart "history-independent" rule. As a matter of fact, both characterizations only differ in one axiom referring to the norm with respect to the emission history (while sharing the norms referring to population and the operational aspects of the allocation process).

We have also characterized the corresponding equal per (BAU) emission rules. The *historical equal per emission rule* also satisfies *historical accountability* (and *resource additivity*), as the *historical equal per capita rule* does. But both rules differ in other axioms. For instance, the *historical equal per emission rule* satisfies *claim upper bound*, whereas the *historical equal per capita rule* does not. On the other hand, the *historical equal per capita rule* satisfies *equal treatment of per-capita equals* and *irrelevance of excessive per-capita emissions*, whereas the *historical equal per emissions rule* does not. Similarly, the *equal per emission rule* satisfies *history independence* (and *resource additivity*), as the *equal per capita rule* does. But the *equal per emission rule* satisfies *claim upper bound*, whereas the *equal per capita rule* does not. And the *equal per capita rule* satisfies *equal treatment of per-capita*

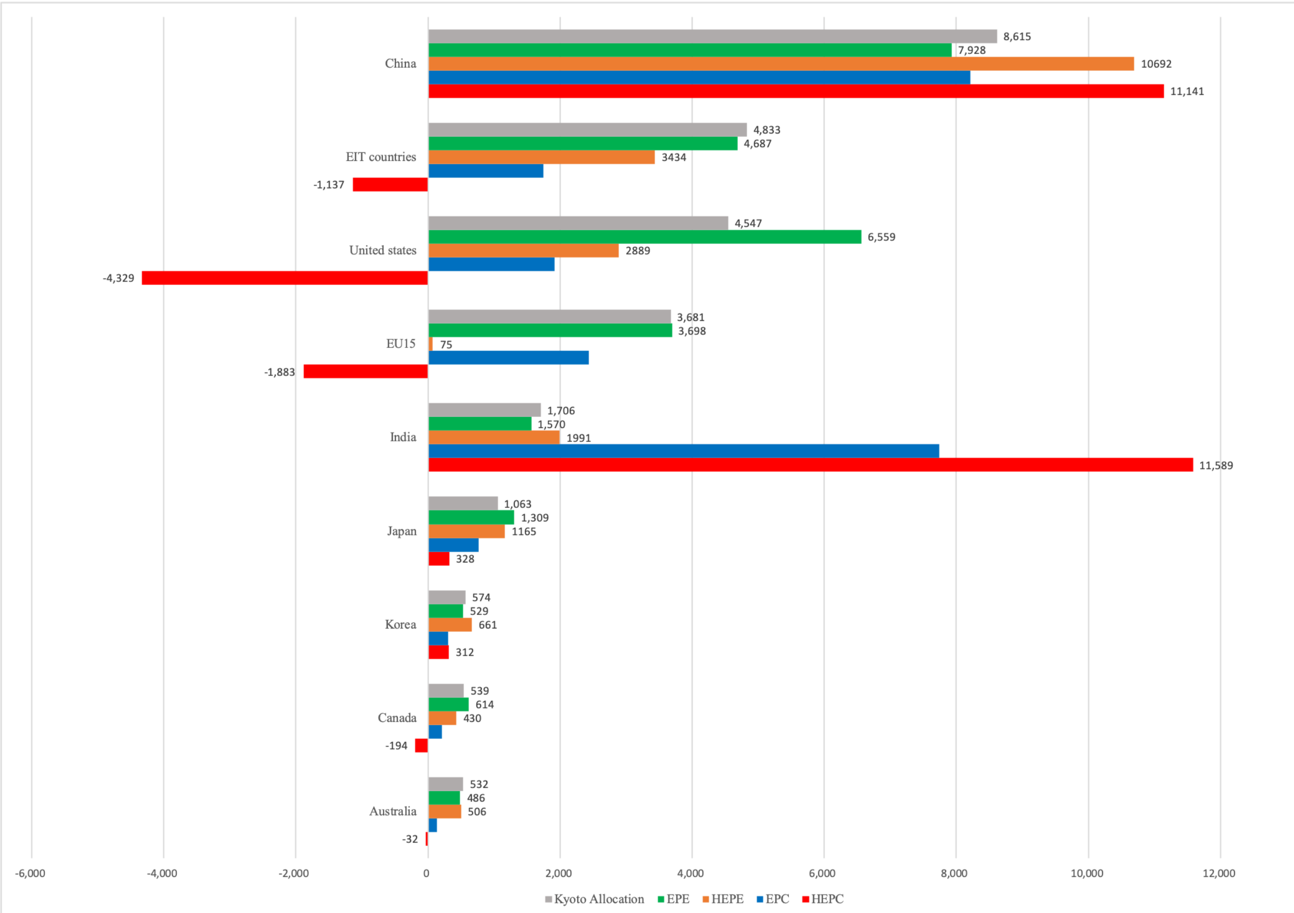

Figure 1: Comparison with the annual CO_2 emission allowances in 2010 under the Kyoto Protocol

equals and *irrelevance of excessive per-capita emissions*, whereas the *equal per emissions rule* does not.

We should acknowledge that, in our model, population is an independent parameter (ν_i) to historical and BAU emissions. As such, the parameter could be interpreted as an alternative characteristic of each country; for instance, GDP. If so, our equal per capita rules could be considered as proportional sharing to GDP, a solution often advocated by rich countries (e.g., Randers, 2012). We, nevertheless, believe that such an interpretation could only be made in purely mathematical terms and that a proper assessment of GDP as a driving factor of GHG emissions would require an extension of our model (in which it would complement, rather than substitute, population). In that augmented model, proportional sharing to GDP might arise as the outcome of a new axiomatic analysis, different to the one considered here. Let us also stress that BAU emissions are strongly correlated to GDP and, therefore, proportional sharing to GDP might look quite similar to our equal per emission rules (with or without historical accountability) characterized in our model. Somewhat related, population is largely correlated to underdevelopment. Hence, the equal per capita rules characterized in our model could embed sharing proportional to the "need of development" with or without historical accountability, a solution often advocated by developing countries (e.g. Agarwal et al. 1991; Singer 2002).

Our model is an augmented version of the standard problem of adjudicating conflicting claims (e.g., O'Neill, 1982; Thomson, 2019). This model refers to one of the oldest problems in the history of economic thought, which can be traced back to Aristotle and the Talmud. Recently, there has been a growing interest to provide extensions of the benchmark model to deal with related complex problems (e.g., Ju et al. 2007, Ju and Moreno-Ternero, 2017 and 2018, Chambers and Moreno-Ternero, 2019). One instance is the so-called rationing problems in the presence of *baselines* (e.g., Hougaard et al., 2012, 2013a, 2013b).[14] Those problems assume the existence of individual baselines, which could be related or not with claims, but that might play a role in the allocation process. As such, historical emissions could be considered the baselines in our setting and, therefore, our model could be considered as a focal rationing problem under the presence of baselines.[15]

[14] See also Moreno-Ternero and Vidal-Puga (2021).

[15] An important advancement of our paper is that our model permits the existence of negative allocations, which was not the case in the existing literature on rationing problems under the presence of baselines.

A crucial aspect of our axiomatic analysis of GHG reduction targets is to bring to the table historical and population considerations, which can hardly be ignored to deal with this problem. As such, our analysis departs from Giménez-Gómez et al., (2016) and Duro et al., (2020), who considered the problem without those considerations and used standard rules from the literature on adjudicating conflicting claims (in its benchmark model) to suggest solutions.

Finally, in our empirical application, we compared the allocation proposed by the Kyoto Protocol with the allocations proposed by our four rules characterized here. The period of applicability of the Kyoto Protocol was set to end in 2020. In order to be able to maintain the international climate protection process after 2020, a new climate agreement was required. This was adopted in 2015 at the COP in Paris as the "Paris Agreement". The Paris agreement removes the strict differentiation between developed and developing countries in the Kyoto Protocol and takes the bottom-up approach to focus on facilitation and promotion of compliance rather than enforcement. The nations submit their national plans of reduction commitment on a voluntary basis. Hence nationally determined contributions (NDC) differ widely across nations in terms of national targets and base years among others and are subject to no agreed enforcement scheme. There are also numerous critical obscurities in the proposals by major participants including the US, EU, China and India. In particular, China and India do not even provide absolute reduction target (e.g., Seo, 2017). Thus, the agreement can hardly be represented by an allocation rule in our model and compared with our allocation rules. To extend our analysis for the assessment of the Paris agreement, it is necessary that major emitters in both developed and developing regions implement their NDC pledges and the agreement come into effect, which may take a while considering the current sluggish progress (for instance, see the critical comments by Victor et al., 2017).

6 Appendix

We provide a useful lemma, which pertains to the problems with zero target emission ($E = 0$) and that it is invoked in the proof of Theorem 1 presented above.

Lemma 5. *If a rule f satisfies historical accountability, equal treatment of per-capita-equals, irrelevance of excessive per-capita emissions and resource* *additivity, then* $f(h, c, \nu, 0) = -h$*, for each* $(h, c, \nu, 0) \in \mathcal{P}$*.*

Proof. Let f be a rule satisfying the four axioms. We shall prove the lemma by mathematical induction with regard to the number of communities with a positive historical emission.

Step 1. For each $P \equiv (h, c, \nu, E)$, with $h = \mathbf{0}_n$ and $E = 0$, $f(P) = \mathbf{0}_n$.

Note that, when $E = 0$, all current emissions are excessive. Let c' be such that for each $i \in N$, $c'_i = \nu_i \lambda$ with $\lambda > 0$, and $P' \equiv (h, c', \nu, E) = (\mathbf{0}_n, c', \nu, 0)$. Then, by *irrelevance of excessive emissions*, $f(P) = f(P')$. By *equal treatment of per-capita-equals*, all communities get equal per capita amounts at P'. This means that, when $E = 0$, $f(P') = \mathbf{0}_n$. Hence, $f(P) = \mathbf{0}_n = f^{HEPC}(P)$.

Step 2. Suppose, by induction, that there is $k \in \{0, 1, \ldots, n-1\}$ such that for each $P \equiv (h, c, \nu, E) \in \mathcal{P}$ with $E = 0$, if there are at most k communities with positive historical emissions, $f(P) = -h$. Let $P \equiv (h, c, \nu, E) \in \mathcal{P}$ be such that $E = 0$ and there are $k + 1$ communities with positive historical emissions. Without loss of generality, let $\{1, \ldots, k + 1\} \subseteq N$ be the set of communities with positive historical emissions, that is, for each $i \in N$, if $i \leq k + 1$, $h_i > 0$, and if $i \geq k + 2$, $h_i = 0$. Let $i \in \{1, \ldots, k + 1\}$. By *historical accountability*,

$$f_i(h, c, \nu, E) = f_i((0, h_{-i}), c, E) - h_i.$$

By the induction hypothesis, $f_i((0, h_{-i}), c, \nu, E) = 0$. Hence, for all $i \in \{1, \ldots, k + 1\}$,

$$f_i(h, c, \nu, E) = -h_i. \tag{3}$$

Next, as $E = 0$, current emissions of all communities are excessive. Let c' be such that for each $j \geq k + 2$, $c'_j \equiv \nu_j \lambda$ with $\lambda > 0$, and for each $i \leq k + 1$, $c'_i \equiv c_i$ and $P' \equiv (h, c', \nu, E)$. Then, by *irrelevance of excessive per-capita emissions*, $f(P) = f(P')$. So, applying *equal treatment of per-capita-equals* to P', $f_{k+2}(P)/\nu_{k+2} = \cdots = f_{|N|}(P)/\nu_{|N|}$, which together with (3) implies $f_{k+2}(P) = \cdots = f_n(P) = 0$. Therefore, $f(P) = -h = f^{HEPC}(P)$. □

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