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Decarbonization of academic laboratories: On the trade-offs between CO₂ emissions, spending, and research output

Xavier Capet^{a,*}, Olivier Aumont^{a,b}

^a LOCEAN, CNRS/IRD/Sorbonne Université/MNHN, 4 place Jussieu, Paris, 75005, France

^b Labospoint5, France

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ABSTRACT

University laboratories and research institutes are progressively engaging in reducing greenhouse gas (GHG) emissions from their operations. It can be difficult to target all sources of GHG emissions at once, given the diversity of problems posed by each source individually. However, targeting only one or a subset of emissions sources can lead to reallocation of expenditures and thus transfers between emissions items when the financial budget is constant. A simple toy model with 2 or 3 expenditure items and 2 classes of laboratory personnel allows us to explore the communicating vessels effects associated with the partial decarbonization of research entities in different scenarios. More generally, the model highlights the trade-offs between CO₂ emissions, expenditures, and output/research production. Decarbonization measures must be carefully planned based on thorough identification and quantification of direct emissions sources inside and outside the laboratory. Examples pertaining to air travel and use of labware are discussed in detail. Redefining expectations in terms of research production could allow for a greater emphasis on environmental constraints but this requires institutional as well as ethical transformations.

1. Introduction

Mitigating climate change is widely recognized as one of the most critical issues currently faced by human societies. Emissions of greenhouse gases by human activities have already caused a warming of about 1.1 °C on average relative to the preindustrial period (IPCC, 2021). Limiting this warming to 1.5 or 2 °C as stated by the Paris Agreement in 2015, which has been adopted by nearly all nations, requires to strongly and quickly cut these emissions and reach carbon neutrality within the next few decades (Tollefson, 2018; Liu et al., 2023). In 2021, 124 countries have declared their intention to become carbon neutral by 2050 or 2060 (Chen, 2021). Achieving this objective requires profound changes in all sectors, combining social, environmental, economical and technological measures (Chen et al., 2022; Figueres et al., 2017; Alfredsson et al., 2018).

Awareness of professional environmental footprint associated with academic research (AR) activities is increasing, as it does in many other sectors. Indicative of this is the steady growth of the literature on the carbon footprint of academic research and higher education (Valls-Val and Bovea, 2021; Li et al., 2021). A large and increasing number of universities and institutions have calculated, at least partially, their

carbon footprint (Valls-Val and Bovea, 2021; Helmers et al., 2021). Several research communities are quite advanced on the quantification of their impacts (e.g., van der Tak et al., 2021; Knödseder et al., 2022; Bloom et al., 2022; Burnett et al., 2016). Diverse mitigation measures have been proposed and often implemented by research institutions, such as switching to renewable energy (Mustafa et al., 2022; Stevens et al., 2020), improving building insulation (Ozawa-Meida et al., 2013; Mendoza-Flores et al., 2019), favouring videoconferencing (van Ewijk and Hoekman, 2021; Skiles et al., 2022) and invest in local or distant carbon offsetting (Adbullah et al., 2019; Helmers et al., 2021). As far as we know, all AR entities with hard carbon budget objectives (e.g., 50 % emission reduction, net zero) plan to rely on offsetting (many U.S. universities including UCs; <https://sustainability.ucdavis.edu/goals/climate/>; <https://sustainability.uci.edu/sustainablecampus/climate-and-energy/>; https://www.ucop.edu/sustainability/_files/carbon-neutrality2025.pdf).

Reducing the carbon footprint is generally not the only goal of decarbonization policies. Several other objectives are also considered such as cost efficiency, competitiveness, and fairness (Creutzig et al., 2012; Breetz et al., 2018; Jin et al., 2020). For instance, negative impacts on critical economic outcomes are often invoked as a reason to reject

* Corresponding author.

E-mail address: xavier.capet@locean.ipsl.fr (X. Capet).

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ambitious decarbonization plans (Paterson and P-Laberge, 2018). As a consequence, reducing its carbon footprint requires to consider trade-offs among relevant outcomes for the considered activity or entity and find an optimal solution. The outcomes and trade-offs of ten decarbonization policies have been recently reviewed for large socio-economic systems, such as states (Peñasco et al., 2021). To our knowledge, a similar investigation is lacking for the sector of academic research, in particular at the scale of a research entity such as a laboratory (but see, Gratiot et al., 2023).

The main objective of our study is to expose some of the trade-offs underlying AR decarbonization. More specifically, we are concerned with the interplay between spending (B), material and immaterial production (O), and environmental impact (E) of a research entity trying to decarbonize its research by implementing changes at its own scale. Given the complexity of the task, including social resistance to changes, incremental strategies are frequently favored, with the adoption of decarbonization measures that are limited in scope, e.g., by trying to reduce purchases of one or a few spending items. Typical spending items covered by the study are lab equipment and consumables, as well as transport services. Workforce adjustments are also considered. This work is deemed most relevant to inform AR small- and medium-size entities such as research labs or institutes, and project consortia. Indeed, a study by De Paepe et al. (2023), which examined the carbon footprint of purchases in research laboratories, found that mitigation strategies should strongly depend on the specificity of the research entities. This suggests thus that a relevant scale to implement mitigation strategies is that of a research laboratory. Nevertheless, the challenges faced by such entities are quite similar irrespective of their field and size, hence the general purpose of our work. The approach we propose is based on three core equations decomposing B, O, and E (here, GHG emissions) by a given research entity into four items. The decomposition attempts to make as explicit and transparent as possible the trade-offs that do exist between B, O and E.

Applied to a few decarbonization case studies, the framework we lay out (equations and data set) allows us to draw attention on some mitigation delicacies that AR is likely to face. These primarily include communicating vessels effects, in which AR emissions would be displaced rather than eliminated. These also include more subjective issues pertaining to coupling between AR and the rest of society (e.g., equitable access to low-CO2 resources and services) as well as the potential need for more profound social/institutional changes in how research output is defined and evaluated. Indeed, while building the simple model used in this work, we had in mind two messages frequently heard in many research communities since they have started to self-question their environmental impact: 1) how are we going to be able to reduce environmental impacts while maintaining our research's visibility and level of excellence (Eriksson et al., 2020a; Kreil, 2021; Fahey and Kenway, 2010, in relation to deaeromobilitation)? 2) shouldn't we be asking more money to transition if the change we have to make to become more virtuous costs additional money (i.e., the green premium) (Li et al., 2021)?

The outline of this paper study is as follows. The conceptual model and how it will be used are described in section 2 (Materials and Methods). Model applications on various decarbonization case studies are presented in section 3, with two concrete applications to the issues posed by air travel and disposable labware. A discussion section follows (section 4) that revisits key aspects of the ecological transformation of academia (including questions 1 and 2 above) by taking advantage of the model formalism. Concluding remarks are offered in section 5.

2. Materials and Methods

2.1. General model framework

We are interested in the coupling and joint evolution of total GHG emissions (E), budget/expenditure (B) and research output (O) for a

research entity, typically a laboratory or an institute (but the framework we lay out below could a priori be complexified somewhat to inform transformation at larger scales, such as a university). A research entity here refers to an organization that exhibits a specific focus on a particular scientific field of research, for instance climate science, economics, health. Additionally, when examining mitigation measures implemented at the entity level, it is essential for these entities to have a governance system, such as a direction committee or steering assembly. In the context of the French research system, these entities typically consist of 10–1000 people, which testifies for the large range within this scope.

Our framework is defined by the following core assumptions:

- There are two stylized classes of personnel, high (1) and low-CO2 emitters (2) whose number and salary per individual are respectively denoted P_i and S_{P_i} , where $i = 1$ or 2. Low-CO2 emitters are typically support staff. Scientists (professors and researchers with or without tenure status) represent the archetypal high-CO2 emitters.
- Scientists purchase two classes of goods and/or services (hereafter GS): one class that will be targeted by emission mitigation measures (denoted by the subscript t in the mathematical expressions and referred to as TGS in the text) and the other that will not (denoted by the subscript nt and referred to as NTGS). The associated expenditure rates (in euros per person) are S_t and S_{nt} . Similarly, their associated emission factors (in tons of CO2 per keuro) is noted F_t and F_{nt} . In Section 3.2 an additional class corresponding to the replacement of TGS by substitute GS (SGS) is also introduced.
- Both classes of personnel are responsible for identical baseline emissions E_{base} . For simplicity the cost of the baseline goods and services is incorporated into S_{P_1} and S_{P_2} .
- There is a linear relationship between research output on the one hand, and consumption of GS (both targeted and non targeted) as well as money spent on human resources (P_1 and P_2) on the other hand, with utility factors denoted by U and the appropriate subscript.
- For completeness the AR field can receive and/or exchange money and/or GHG emission credits with other actors at rates B_{ex} and E_{ex} , e.g., if it purchases carbon offsets or secures additional fundings as part of its decarbonization strategy. We assume zero B_{ex} and E_{ex} throughout this work unless otherwise stated. Although there may be isolated exceptions, the use of $B_{ex} = 0$ is consistent with the fact that an approximately constant fraction of national GDPs is devoted to academic research.

Our core set of equations is thus:

$$B = S_t P_1 + S_{nt} P_1 + S_{P_1} P_1 + S_{P_2} P_2 + B_{ex} \quad (1a)$$

$$O = S_t P_1 U_t + S_{nt} P_1 U_{nt} + S_{P_1} P_1 U_{P_1} + S_{P_2} P_2 U_{P_2} \quad (1b)$$

$$E = S_t P_1 F_t + S_{nt} P_1 F_{nt} + (P_1 + P_2) E_{base} + E_{ex} \quad (1c)$$

In practice the equation set (1a-c) will be used to study finite-amplitude perturbations about an existing system state so linearization cannot be formally justified. Using a linear expression for research output is perhaps the least robust assumption we make because research output depends in a very subtle way on many interrelated factors (Ramsden, 1994; De Witte and Rogge, 2010). Furthermore, there are many discussions on how to define and thus quantify it (e.g., Karagiannis and Paschalidou, 2017; Witte and López-Torres, 2017). Our framework would for instance be ill-suited to study the decarbonization of a research unit whose research activity critically depends on a hard-to-replace high co2 intensity resource (high F_t , U_t much larger than that of all other resources). Keeping this in mind, we will be cautious when interpreting our findings with respect to research output (and see the Discussion section).

Computation of the GHG emissions induced by an organization such as a laboratory, a university or a research institute is less well codified

than for products (Robinson et al., 2015). However, several regulatory frameworks have been developed, in particular the Greenhouse Gas Protocol (GHG protocol) (WBCSD, 2011). This protocol is particularly well suited for AR as it accounts for all possible indirect emissions (scope 3) which have been found to be of primary importance in AR (Valls-Val and Bovea, 2021). In the rest of this study, we favor decarbonization scenarios in which the budget of the research unit is held constant. In a context where the overall AR budget would change substantially (to the direct detriment or benefit of other sectors), accounting for edge/ripple effects across activity sectors might become essential (see Section 4). In this model the idealized research entity is hypothesized to have complete freedom to redistribute its budget among expenditure items including salaries. But the results we obtain may still be relevant in a context where control is partial.

The choices and assumptions we made to derive our set of equations have important implications in terms of problem framing, findings and interpretations. They also certainly describe in a very simplistic way the complex aspects and the internal and external interactions of a research unit. Furthermore, research entities exhibit a very large diversity in terms of size, research field, practices, and equipment needed. This extensive diversity is encapsulated in the expenditure rates S , F , and U whose values are at least partly bound to the considered research entity. Nevertheless, we consider them suitable for exposing the zero-order realities that research laboratories, institutes and projects face as they engage in the reduction of their environmental footprint.

2.2. Mitigation approaches

We explore the implications of mitigation approaches idealized as a two-stage process: a mitigation stage aimed at reducing the emissions associated with a target good/service; this first stage can then be followed by a redistribution stage in which financial resources freed, or mobilized, and/or received as part of the mitigation stage are reallocated within the research unit. The first stage will generally consist in changing a small number of factors in the set of equations (1a)–(1c) (see next section). The second stage will induce communicating vessel effects on budget and emissions. Due to the simplified form of our equations, the two stages are merged (in time) and idealized as one single set of changes/adjustments (denoted using the symbol δ) relative to an initial state with no mitigation.

2.3. Model data: emissions and emission factors

Our model relies on monetary emission factors F . These factors may be obtained by using Environmental Extended Input-Output (EEIO) based modeling (Minx et al., 2009). This approach has proven very useful to compute the carbon footprint of complex entities such as a university or a research centre (e.g., Lenzen et al., 2010; Larsen et al., 2013). In particular, it allows the accounting of non-physical flows for which other approaches such as Life Cycle Assessment are difficult to apply (Ward et al., 2018; Crawford et al., 2018). Furthermore, the sector of public academic research is governed by financial rules laid down by the public authorities, which lead to precise and standardized accounting of expenses.

Several databases have been produced by EEIO models, some of them providing multi-regional information (Druckman and Jackson, 2009; Tukker et al., 2009; Kitzes, 2013). Here, our main objective is to propose a simple general and formal framework useful for exploring the consequences of implementing measures to reduce the carbon emissions of a research unit. As a consequence, a precise estimation of the monetary emission factors is not critical in our general case but should be done when applied to a specific real case. However, as we will illustrate our framework with some examples, some emission factors have been selected.

The average emission factor of a research entity was estimated to be between 0.4 and 0.8 kgCO₂e/€, including emissions from all scopes

(Larsen et al., 2013; Townsend and Barrett, 2015). An analysis performed on the purchases of a set of about 110 French laboratories (excluding emissions from scopes 1 and 2 as well as air travel) evaluated a mean emission factor of 0.33 ± 0.07 kgCO₂e/€ (De Paepe et al., 2023). Here we adopt a value of 0.4 kgCO₂e/€.

The emission factor for air transportation is highly variable (e.g., see Fig. 2 in Ciers et al. (2018)) and tends to increase with the distance traveled. An absolute upper bound shall be when airplane ticket fee covers only the cost of fuel operations which yields ~ 6 kgCO₂e/€ for a kerosene price of 80 €/barrel (EF of jetfuel is 3.05 kgCO₂e/l and a barrel is 159 l). In contrast the value of 1.1 kgCO₂e/€ given by the U.S. EPA (EPA, 2020) can be considered as a lower bound, corresponding to 20% or less of the ticket fee spent on kerosene. An intermediate value of 2.5 kgCO₂e/€ associated with a 50% share of the ticket fee spent on kerosene is plausible for long-haul flights and perhaps some shorter low-cost flights (Koopmans and Lieshout, 2016). None of these numbers includes indirect radiative effects (Lee et al., 2021) whose mitigation will only be briefly discussed.

The factors for laboratory glass and plasticware are also very variable. The U.S. EPA database gives 0.8 and 0.6 kgCO₂e/€ respectively. However, for very specialized products whose price can be very high, emission factors can be much lower, as low as 0.1 kgCO₂e/€ for single-use plastics for instance (De Paepe et al., 2023).

Baseline emissions are induced by all activities that are not specific to the research work. They include for instance heating and air conditioning, commuting, and building operations. They should vary greatly between research units depending on local climate, building insulation and heating/cooling usage, dietary habits of the employees, the energy mix used to produce electricity, etc. Emissions per staff member are estimated to be generally between 2 and 5 tCO₂e/person in an office in a developed country (van der Tak et al., 2021; El Geneidy et al., 2021; Cambaz et al., 2018). Choosing an intermediate value of 3 tCO₂e/person and a salary figure of 30 k€/y we obtain a P2 base emission factor of $E_{base}/S_{P_2} = 0.1$ kgCO₂e/€. On the basis of these sketchy estimates, emission factor values used in this study are selected as shown in Table 1.

3. Stylized decarbonization cases

In this section, we present a variety of real life decarbonization initiatives (implemented or considered for implementation) in our toy model framework.

3.1. Restrictions/quotas/rationing on TGS

This mitigation approach is represented as a combination of: Stage 1) a quota on TGS *individual emissions* leading to a reduction of S_i by an amount $\delta S_i < 0$; Stage 2) a reallocation of the money saved on TGS expenditures under the constraint that total research expenditures B are constant. This could typically be air travel-related emissions restrictions implemented on its own initiative by an AR entity.

3.1.1. Adjustment involving NTGS purchase rate

In this case, adjustment during stage 2 consists of a transfer of purchases from TGS to NTGS. Eq (1a) implies that $\delta S_{nt} = -\delta S_i$, hence, the

Table 1

Range of emission factors for different items relevant to academic research activities in kgCO₂e/€.

Item	F_{min}	F	F_{max}
Air travel	1.1	2.5	6
Plastic labware	0.05	0.6	
Glass labware		0.8	
purchased GS (excl. air transport)	0.26	0.4	0.44
AR personnel baseline (E_{base}/S_{P_2})	0.07	0.1	0.17

following set of constraints:

$$\delta E = \delta S_t P_1 (F_t - F_{nt}) \quad (2a)$$

$$\delta O = \delta S_t P_1 (U_t - U_{nt}) \quad (2b)$$

The outcome in terms of CO₂ emissions depends on the difference in CO₂e intensity between TGS and NTGS as illustrated in Fig. 1. Effective mitigation approaches should restrict the purchase of CO₂e-intensive goods/services (air travel, gases, common chemicals and to a lesser extent, disposable plastic labware; see Table 1). If stage 2 adjustment consists of expenditure transfers spread over an average GS basket, F_{nt} is approximately equal to 0.4 kg CO₂e/€. In the case where TGS is plastic labware (CO₂e intensity of 0.6 kg CO₂e/€ or less), at least 2/3 of the emission reductions is cancelled by this communicating vessel effect and total GHG emissions could even increase in some cases (see Sec. 3.3 for more elaboration). Note that the overall reduction is also proportional to δS_t . This highlights the particular difficulty faced by a research entity emitting most of its CO₂ through the purchase of large amounts of relatively low CO₂e-intensive GS.

The outcome in terms of research output O depends on the respective utility of TGS and NTGS. Let us consider the important example of replacing short-haul flights with train travel, i.e., when TGS can be substituted by some NTGS. Some scientists tend to consider that rail travel can be used more efficiently for work than air travel (Quinton, 2020a). In this case, then, one may have $U_{nt} > U_t$ or at least $(U_t - U_{nt})/U_t$ small compared to $(F_t - F_{nt})/F_t$ at the aggregated level of the research entity. Hence there could be limited or even positive output effects associated with decarbonization. In cases where TGS are essential and cannot be substituted, the linearity assumption used for O presumably breaks down and comparing U_{nt} to U_t has little meaning. This may be the case for example if the definition of O values scientific advances inherently associated with remote field work for which videoconferencing is of no utility (Smidvik et al., 2020; Bjørkdahl and Franco Duharte, 2022).

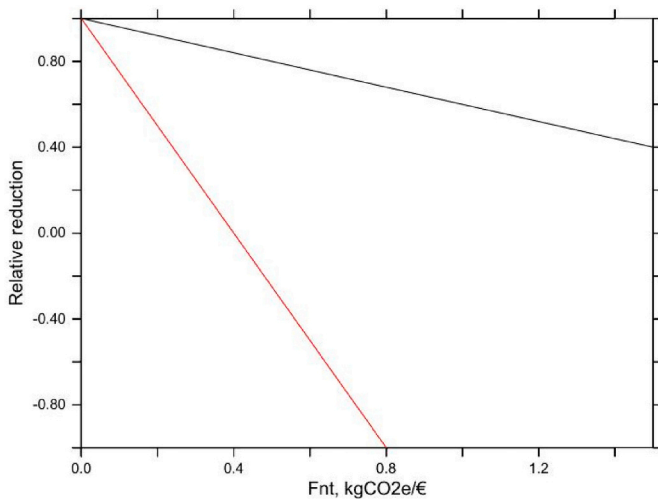


Fig. 1. Relative reduction of the total emissions with a quota/rationing compared to the case where there is no transfer of purchases from TGS to NTGS. Black line and red line correspond to cases where air travel and laboratory equipment are subject to quotas respectively. F_t is set to 2.5 kgCO₂e/€ for air travel and 0.4 kgCO₂e/€ for laboratory equipment (Table 1). A value of 0 means that the reduction is completely cancelled out by the transfer to NTGS. A value of -1 indicates that the transfer to NTGS leads to twice as many emissions as original TGS emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.2. Adjustment involving P₁ hiring

To illustrate the potential complexity of communicating vessel effects, we consider a decarbonization strategy analogous to that of the previous section except that stage 2 now consists of recruiting additional P₁ scientists. In practice, this could mean identifying key foreign collaborators and have them join the research entity under consideration for long-term stays funded by reduced air travel.

This additional P₁ workforce is entitled to purchasing both NTGS and TGS (the latter with the same restrictions as the other personnel). Assuming constant B, we draw δP_1 from Eq. (1a):

$$\delta P_1 = -\frac{\delta S_t P_1}{S_t + \delta S_t + S_{nt} + S_{P_1}}$$

This allows us to express the changes in CO₂e emissions and output δE and δO after all adjustments are considered:

$$\delta O = \delta S_t P_1 \left[U_t \left(1 - \frac{S_t + \delta S_t}{S_t + \delta S_t + S_{nt} + S_{P_1}} \right) - \frac{U_{nt} S_{nt} + S_{P_1} U_{P_1}}{S_t + \delta S_t + S_{nt} + S_{P_1}} \right]$$

$$\delta E = \delta S_t P_1 \left[F_t \left(1 - \frac{S_t + \delta S_t}{S_t + \delta S_t + S_{nt} + S_{P_1}} \right) - \frac{F_{nt} S_{nt} + E_{base}}{S_t + \delta S_t + S_{nt} + S_{P_1}} \right]$$

Expressions for δE and δO are similar. They both involve a term due to δS_t change at stage 1 plus two stage 2 effects which tend to increase δE and δO (for a negative δS_t), i.e., they play detrimentally with respect to CO₂e emissions and positively with respect to research output. The similarity with the equations derived in the previous case can be readily seen by introducing the weighted average emission intensity F_{w1} and utility U_{w1} associated with NTGS and P₁ emissions/activities.

$$F_{w1} = \frac{F_{nt} S_{nt} + E_{base}}{S_{nt} + S_{P_1}}$$

$$U_{w1} = \frac{U_{nt} S_{nt} + U_{P_1} S_{P_1}}{S_{nt} + S_{P_1}}$$

where the weights depend on budget expenses for personnel category 1. Equations for δE and δO above can then be manipulated and yield:

$$\delta O = \delta S_t P_1 (U_t - U_{w1}) \frac{1}{1 + \frac{\delta S_t}{S_{nt} + S_{P_1}}}$$

$$\delta E = \delta S_t P_1 (F_t - F_{w1}) \frac{1}{1 + \frac{\delta S_t}{S_{nt} + S_{P_1}}}$$

The presence of the weighted averaged terms (U_{w1}, F_{w1}) reflects communicating vessel effects whereby restrictions on TGS spending feed emission/output sources associated to the supplementary P₁. The ratio on the right-hand side of the two equations above indicates the impact of newly recruited P₁ scientists on TGS-related emissions and production. In the case of a collective quota (which is not made a function of the number of P₁ scientists) instead of an individual quota, this ratio would vanish. The limit situation where adjustment effects exactly annihilate stage 1 emission reductions is obtained for $F_t = F_{w1}$, which is independent of S_t and δS_t .

In a similar fashion, the net outcome in terms of research output heavily depends on the utility of TGS U_t relative to U_{w1} . Note that δO can be rewritten (as in section 3.1.1):

$$\delta O = \delta E \frac{U_t - U_{w1}}{F_t - F_{w1}} \quad (3)$$

This relationship encapsulates the trade-offs between emission reduction and its effects on research output. In most cases, it cannot be utilized as is because U_t and U_{w1} cannot be quantified. But it still simply expresses the fact that goods and services with high CO₂ intensity and low-moderate perceived utility are obvious priority targets for mitigation action.

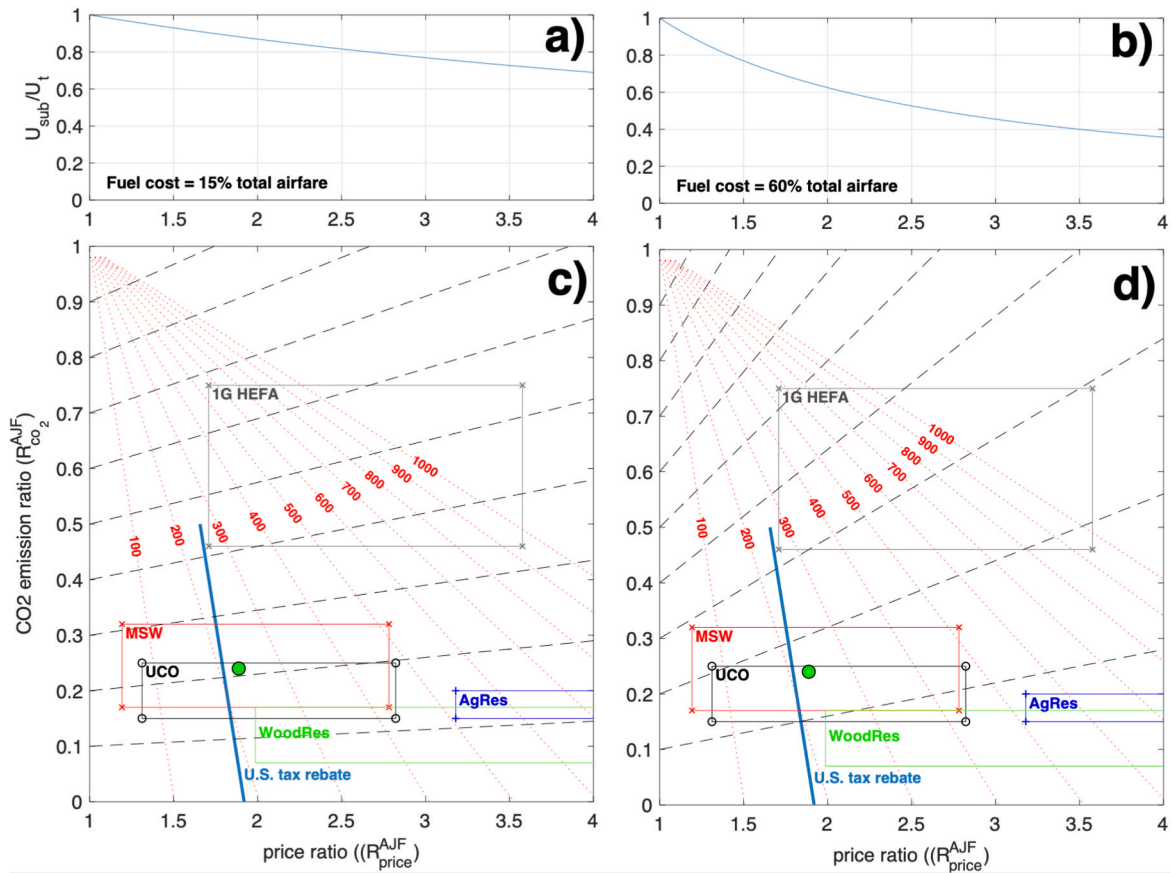


Fig. 2. Price and CO₂ emission ratios relative to fossil kerosene associated with different low-carbon jet fuel. Isocontours of F_{AJF}/F_t are represented as black dashed lines with the isocontour values equal to ordinate at origin, i.e., $R_{AJF}^{CO_2}$ for $R_{AJF}^{price} = 1$. Isocontours of cost of avoided ton of CO₂ are represented as red dotted lines with labels in euros per ton CO₂. Characteristics at maturity for different technologies/feedstock are shown as rectangles: hydrotreated esters and fatty acids (HEFA) based on edible oilseed (1G HEFA; 1st generation AJF); used cooking oil HEFA (UCO); Fischer-Tropsch gasification of municipal solid waste (MSW); conversion of agriculture residues (AgrRes) or woody biomass residues (WoodRes). The green filled circle indicates the expected characteristics of multi-billion liters of jet fuel blend pre-purchased by major airlines at the end of 2021 to be delivered in the coming decade. The light blue line displays the characteristics of an alternative jet fuel whose premium would be fully compensated by the U.S. tax credit measure on alternative jet fuel (Inflation Reduction Act of 2022) with a reference fossil jet fuel price of 80 \$ per barrel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Substitution of TGS by alternative GS and P₂

3.2.1. General considerations

In this case, activities using TGS can be substituted by similar activities using SGS (standing for substitute goods and services) but with the consequence of being more human labor intensive. Hence, additional P₂ have to be recruited by the research entity. This case could typically correspond to the (re)introduction of reusable labware as a replacement for disposable plastic items used in lab experiments. Doing so while trying to minimize the impacts on the research output O would require purchasing, for instance, autoclaves and dishwashers as well as hiring additional P₂ technical staff (Banks et al., 2020). An alternative would be to reduce U_{P₁} because P₁ scientists have to perform the cleaning and decontamination of labware themselves.

We start by assuming that the substitution involves no modification in cost (hence no stage 2) and subsequently relax this assumption. We introduce $\alpha = -\delta S_{sgs}/\delta S_t$ the fraction of money formerly spent on TGS that is used to buy SGS, the rest being spent on additional P₂ staff. α is close to 0 for decarbonization approaches that are intensive in human labor. Conversely, $\alpha = 1$ typically represents a decarbonization pathway in which TGS can be replaced one by one with a low-carbon alternative.

Introducing α into the relevant equations for δO and δE , we obtain the following system:

$$\delta O = \delta S_t P_1 (U_t - (\alpha U_{sgs} + (1 - \alpha) U_{P_2})) \quad (4a)$$

$$\delta E = \delta S_t P_1 \left(F_t - \left(\alpha F_{sgs} + (1 - \alpha) \frac{E_{base}}{S_{P_2}} \right) \right) \quad (4b)$$

Strictly speaking, linear Eq. (4a) implies that SGS and P₂ technical staff are interchangeable in terms of overall utility and that different values of α correspond to different viable substitution approaches to TGS. This may or may not be the case depending on the decarbonization item at stake. If only one low-carbon alternative exists, α is determined uniquely. If there are several alternatives, α can take different values, although one of them will be preferable for a given metric, e.g., the one with the least impact on output per avoided CO₂e emission $\delta O/\delta E$ (or equivalently the one with the minimal cost of avoided carbon emission $\delta B/\delta E$ - in €/ton CO₂e - if the constraint were to hold output O constant).

Noting U_{sub} and F_{sub} the utility and CO₂e intensity of a decarbonization/substitution option, we rewrite our system 4:

$$\delta O = \delta S_t P_1 U_t \left(1 - \frac{U_{sub}}{U_t} \right) \quad (5a)$$

$$\delta E = \delta S_t P_1 F_t \left(1 - \frac{F_{sub}}{F_t} \right) \quad (5b)$$

System 5 can be valid even when the linearization assumption underlying Eq. (1b) and System 4 is not.

A generalization is to consider that AR budget transfers (stage 2) are being made, typically to optimize δO . Specifically, we are now assuming

that SGS and P_2 expenditures are increased or reduced by a factor β to the detriment/benefit of non targeted GS, while maintaining B constant. We thus have $\delta S_{\text{SGS}} = -\alpha \beta \delta S_t$ and $\delta P_2 S_{P_2} = -(1-\alpha) \beta \delta S_t P_1$ and obtain the following equations:

$$\delta O = \delta S_t P_1 U_t \left(1 - \frac{\beta U_{\text{sub}} + (1-\beta) U_{\text{nt}}}{U_t} \right) \quad (6a)$$

$$\delta E = \delta S_t P_1 F_t \left(1 - \frac{\beta F_{\text{sub}} + (1-\beta) F_{\text{nt}}}{F_t} \right) \quad (6b)$$

The meaningful range of values taken by β is between 1 (no budget transfer) and $\beta = U_t/U_{\text{sub}}$ (δO associated with the targeted activity is zero; see Eq. (5a)). As we shall see below, situations exist in which $U_{\text{sub}} > U_t$ and additional NTGS can be purchased with the budget freed by the substitution of TGS with SGS ($\beta < 1$; $\delta O > 0$). Frequently though, we expect $U_{\text{sub}} < U_t$ and the decarbonization will imply restrictions on SGS and/or NTGS purchase.

3.2.2. Green premiums on low-carbon jet fuel

An important limit case concerns green premiums paid, for example, to power supercomputers with low-carbon energy, to fly on low-carbon jet fuel, or to use disposable low-carbon/biosourced labware for lab experiments. This mitigation approach is represented as a purchase transfer between TGS and its low-carbon substitute SGS which is characterized by lower CO_{2e} intensity but also higher price and thus lower utility. In such cases, and unlike the previous examples, e.g., plane versus train, utilities are directly comparable. Thus the problem lends itself to a fully quantitative analysis.

We focus on alternative low-CO₂ alternative jet fuels (AJF) because air transport is a major GHG emission source for many AR entities (e.g., Glover et al., 2017; Poom et al., 2017; Ciers et al., 2019) and thus a growing source of concerns (e.g., Schrems and Upham, 2020; Eriksson et al., 2020b; Braun and Rödder, 2021; Tseng et al., 2022; Ben Ari et al., 2023). The production and usage of AJF (first so called biofuels and then increasingly synth kerosene) are projected to increase markedly in the coming years as a means to reduce the carbon footprint of aviation (Sgouridis et al., 2011; Kousoulidou and Lonza, 2016; Wise et al., 2017). Hence, there is a need for AR to elaborate a position on the mitigation role they could play.

The AJF key characteristics relevant to this study are its CO₂ emission ($R_{\text{AJF}}^{\text{CO}_2}$) and price ($R_{\text{AJF}}^{\text{price}}$) ratios relative to fossil kerosene. Fig. 2 shows the $(R_{\text{AJF}}^{\text{price}}, R_{\text{AJF}}^{\text{CO}_2})$ subspace occupied by the most promising 2G (non edible) biojet fuels and 1G oilseed HEFA-SPK (hydrotreated esters and fatty acids synthesized paraffinic kerosene), currently the dominant AJF on the market (Susan and Jack, 2021). The ranges of price ratio for each AJF variant are wide, reflecting the large uncertainty on the production cost and market value achievable for these fuels once the supply chain reaches maturity. On the one hand, innovation and economies of scale should drive prices down (Gutiérrez-Antonio et al., 2017; Santos et al., 2018). On the other hand, AJF with true environmental (and social) benefits will remain scarce and useful for decarbonizing many economic sectors. Therefore, prices cannot be too low. In particular, their price is unlikely to be lower than that of fossil fuel inflated by the price of abated CO₂ when the aviation sector is under some form of emission control mechanism such as the E.U. Cap-and-Trade (Efthymiou and Papatheodorou, 2019).

Assuming a price for fossil jet fuel of 80 \$ per barrel, a price premium equal to what the U.S. federal government will cover with public money (for up to 5% of U.S. aviation fuel burn in 2030; Inflation Reduction Act of 2022) corresponds to $R_{\text{AJF}}^{\text{price}} \sim 1.7$ –2 and a carbon price of 200–300 \$ per abated ton of CO₂. Similar proposals are being pushed by the aviation sector in the E.U. Large purchase agreements of ultra-low carbon AJF have recently been signed by airline companies for the next decade, for a total surpassing 2 billion liters (Bloomberg, 2021; Aemetis, 2021; Neste, 2022). The (incomplete) information found on its characteristics

suggests $R_{\text{AJF}}^{\text{price}} \approx 1.9$ and $R_{\text{AJF}}^{\text{CO}_2} \approx 0.25$ (by combining 60% regular jet fuel and 40% AJF aiming at negative CO₂ intensity of -80 gCO₂/MJ).

Leaving aside the issues of scarcity and equitable access for now (see discussion section), it seems therefore plausible to significantly decarbonize air travel with AJF. What this would entail for AR is also graphically represented in Fig. 2 where we have considered that AR demand of air travel adjusts without budget transfers ($\beta = 1$). Given c_{fuel} the share of fuel cost in aviation operating costs, output and emission reductions, δO and δE can be simply expressed as:

$$\delta O = \delta S_t P_1 U_t \left(1 - \frac{U_{\text{AJF}}}{U_t} \right) = \delta S_t P_1 U_t \left(1 - \frac{1}{1 + c_{\text{fuel}} (R_{\text{AJF}}^{\text{price}} - 1)} \right) \quad (7a)$$

$$\delta E = \delta S_t P_1 F_t \left(1 - \frac{F_{\text{AJF}}}{F_t} \right) = \delta S_t P_1 F_t \left(1 - \frac{R_{\text{AJF}}^{\text{CO}_2}}{1 + c_{\text{fuel}} (R_{\text{AJF}}^{\text{price}} - 1)} \right) \quad (7b)$$

where air transport CO₂ emission sources other than those due to airplane fuel burn have been neglected. c_{fuel} is 0.15–0.25 on average (Brueckner and Zhang, 2010) but it varies substantially due to a number of factors (Atems et al., 2019; Koopmans and Lieshout, 2016). A key factor is flight distance with c_{fuel} typically ranging from 0.2 or less for short-haul to 0.5 or more for long-haul flights. Isocontours of F_{AJF}/F_t for a low (0.15) and a high (0.5) value of c_{fuel} are shown in Fig. 2. These isocontours tilt upward as $R_{\text{AJF}}^{\text{price}}$ increases. This reflects the a priori reduction in usage (and in output) that accompanies price increase, when a constant air transport budget is used to fly with AJF instead of fossil jet fuels. Variations of the utility ratio U_{AJF}/U_t with the price ratio relative to fossil kerosene is shown in Fig. 2 on separate panels for $\beta = 1$. The difference between short- and long-haul flights is evident.

With constant travel spending rates ($\beta = 1$), F_{AJF}/F_t is the CO₂ emission abatement factor. The effect on emissions of any public subsidies offered to compensate for part of the green premium can be graphically represented as a horizontal shift in the diagram associated with a decrease of the $R_{\text{AJF}}^{\text{price}}$ truly felt by AR (all the way to the y-axis if the green premium for AR's air travel is fully offset by "additional budget"). The most detrimental consequences of such a compensation are obviously obtained for large c_{fuel} (compare panels c and d in Fig. 2).

An alternative to obtaining financial compensation for AJF green premiums would be for AR to adjust spending on other GS ($\beta > 1$) in order to limit the reduction in air travel, as captured by the general equations (6a)-(6b). The resulting CO_{2e} emission adjustment would depend on $F_{\text{AJF}} - F_{\text{nt}}$, that is the CO₂ intensity of airfare with AJF minus that of the GS whose purchase rate is reduced to preserve air travel. In the near-future this could have little effect on overall CO₂ emission mitigation provided that 2G AJF with $F_{\text{AJF}}/F_t \lesssim 0.2$ are used so that F_{AJF} becomes comparable to the average CO₂-intensity of GS. But the average CO₂ intensity of other GS will also go down and such communicating vessel effect will become increasingly important when approaching net zero emissions.

The price barrier to decarbonizing AR short-haul flights with AJF may be limited because it will only entail a reduction of $\sim 20\%$ on utility, even for $R_{\text{AJF}}^{\text{price}} \sim 3$. This could be accommodated by an equivalent reduction in air travel, or in another GS purchase or a combination of both. Decarbonizing AR long-haul flights will imply larger penalties and requires a substantial reduction in air travel if spending on that GS item remains constant, on the order of 40% for a price ratio between 2 and 2.5. Usage reduction can actually become a significant part of the overall CO₂ emission reduction, although less so for low CO₂ intensity AJF, as might be expected.

Among AR entities with close ties to distant places and colleagues, some might be tempted to find additional resources to compensate for green premiums on AJF. Within the limits of truly neutral flights this would have no effect on emissions but it would arguably alter AR's

decarbonization in other fundamental ways. Possible guidelines for how the community may want to approach AJF-based mitigation, and in particular where the money to pay for it should come from, are laid out in the Discussion section.

3.2.3. Labware

We finish by attempting to provide insights into the tradeoffs relevant to reduce the carbon footprint of labware (and the volumes of waste to be managed). In some applications, the use of disposable plasticware has been adopted for scientific reasons, such as to reduce potential contamination (Phelps et al., 2020). In these cases, substitution may be more difficult to perform. On the other hand, a brief review of the growing literature on the subject suggests that i) biobased alternatives are being developed to keep using disposable labware (Birajdar et al., 2021; Ferreira-Filipe et al., 2021; Narancic et al., 2020); ii) a switch to

reusable washable plastic or glass laboratory equipment is possible but will frequently require extra manpower (Alves et al., 2021; Banks et al., 2020).

Disposable labware made from bioplastics/low-CO2 plastics are unavoidably associated with additional costs. A complete decarbonization by substitution with 2nd generation feedstock, e.g., cellulosic, is not inconceivable but would presently incur very high premiums and abatement costs (~3000 €/tCO2 Posen et al., 2017) as well as indirect emissions (Escobar and Britz, 2021) whereas partial decarbonization at much lower cost can be achieved by only switching to renewable energy sources in the production process (Posen et al., 2017). Overall, the adoption of low-carbon disposable plasticware i) can be framed as a green premium issue similar to the one detailed in the previous section (but key figures are even more uncertain than for AJF). We focus on ii) which makes for an interesting idealized case study of how Equations

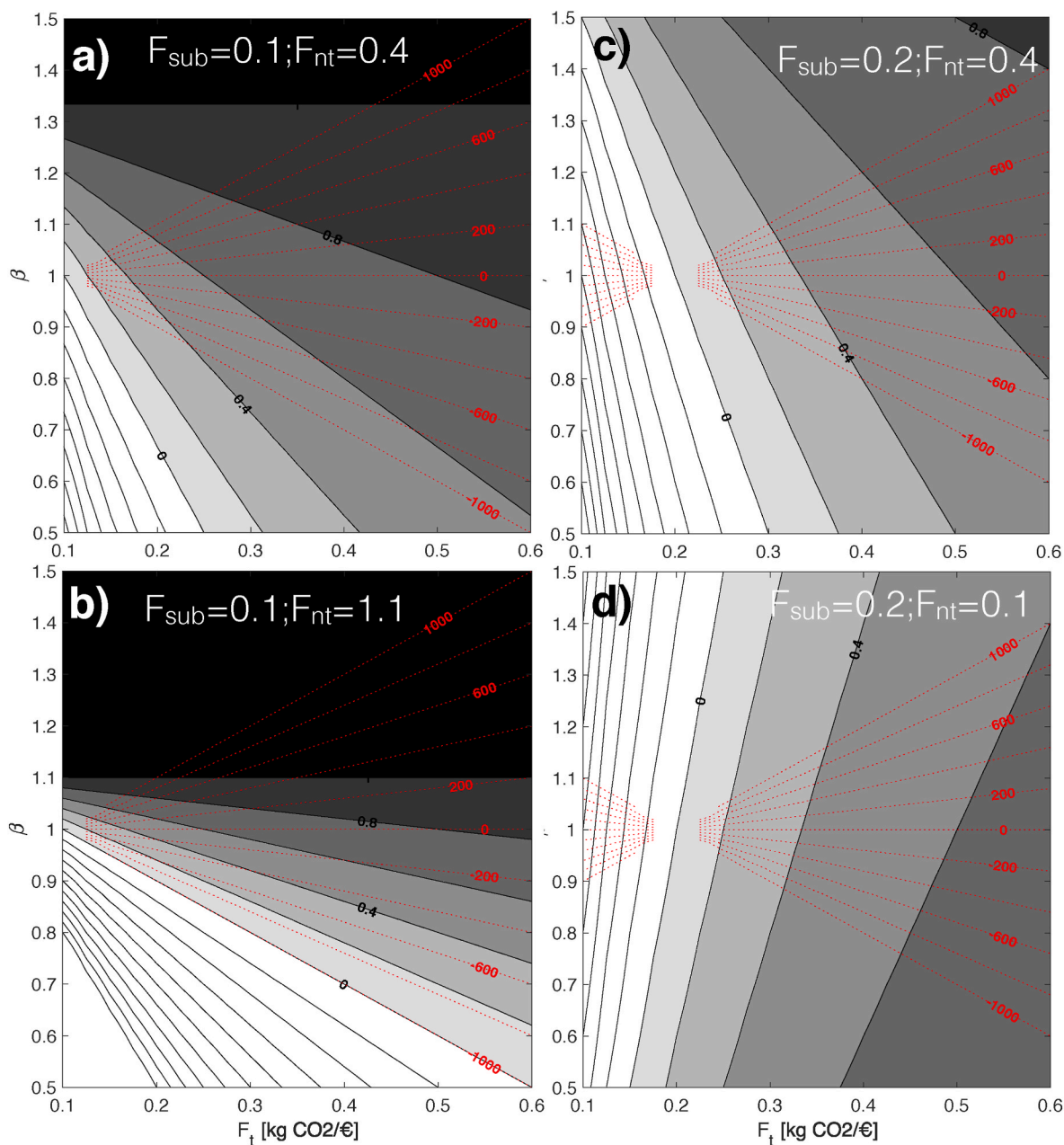


Fig. 3. Net Emission reduction factor (0 = no reduction; 1 = full decarbonization; gray scale with contours every 0.2) and CO2 abatement cost (ignoring communicating vessel effects; red dotted contours with 200 €/kg CO2e increments) for different values of F_{sub} and F_{nt} . CO2 abatement cost is singular at the location where $\beta = 1$ and $F_t = F_{sub}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(6a)-(6b) can help explore the merits of a transition from disposable to reusable labware equipment.

In general the net CO2 emission outcome depends on β and the three carbon intensities in Eqs (6a)-(6b). These quantities are poorly constrained/documentated and context specific (Farley and Nicolet, 2022). They are therefore subject to a parameter sweep (Fig. 3). The range of F_{sub} that we explore is 0.1–0.4 kg CO2e/€. 0.4 kgCO2e/€ is the upper range of the average CO2 intensity of purchases inferred from about 110 french research labs (De Paepe et al., 2023). The lower bound is a typical CO2 intensity associated with P2 personnel in Europe. The 0–0.1 F_{sub} range is excluded to avoid drawing attention on near-perfect decarbonization which will remain beyond reach for some time.

We use three different values for F_{nt} : 0.4 for the reason just mentioned above; 1.1 to present a more radical situation in which budget transfers involve the air travel item; and 0.1 to also explore a situation in which budget transfer involves low-carbon goods and services. The carbon intensity of regular plastic labware typically range from 0.1 (or lower Farley and Nicolet, 2022) to 0.6 kg CO2e/€ (EPA, 2020). High CO2 intensities correspond to low-cost items with limited labor and technology content, for which replacement is most likely to incur additional costs ($\beta > 1$). Low CO2 intensities correspond to laboratory items whose prices primarily reflect labor and technology (and possibly high margins) rather than raw material content. If feasible, their substitution is more likely to be associated with $\beta < 1$, i.e., saving money. The lower left and upper right quadrants of each panel in Fig. 3 are thus a priori those where the more plausible (F_t, β) values shall be located. Inspired by the recent study by Farley and Nicolet (2022), we choose 0.5–1.5 as the range of β values.

Fig. 3 displays isocontours of the emission reduction factor (i.e., the term inside the parenthesis in Eq. (6b), gray scale with full decarbonization in black) and the CO2 abatement cost ignoring communicating vessels $(\beta - 1)/(F_t - F_{sub})$ (red dotted lines) in the (F_t, β) space.

Classically, favorable decarbonization situations correspond to negative or low abatement costs which are obtained for β lower or close to 1 and $F_t > F_{sub}$. Relative to air travel (see previous subsection), the labware CO2 abatement cost can reach large values even for β modestly above 1 because the F_t of plastics is much lower than that of kerosene. But another issue is apparent when $\beta < 1$: a significant part of the CO2 abatement can be annihilated by communicating vessel effects unless $F_{nt} \leq F_{sub}$. This is most evident in subspace $\beta < 1$ of panel b where the money saved through labware substitution is used for air travel and overall decarbonization is strongly reduced even for β not much lower than 1. Conversely, labware substitution with $\beta > 1$ that would be made at the detriment of air travel would yield significant net emission reductions even for $F_t \approx F_{sub}$ (but the CO2 abatement cost of the substitution itself might be considered prohibitive). Obviously, money saved on a particular substitution which is subsequently used to purchase low-carbon GS ameliorates net emission reductions (compare panel c and d for $\beta < 1$). Examples include purchases of other labware substitutions with significant emission saving but extra financial cost or low-carbon jet fuel. In theory, large entities have more leeway to optimize these beneficial communicating vessel effects, provided that they are able to implement redistribution mechanisms among their staff.

Most generally, what Fig. 3 makes clear is that the CO2 abatement cost cannot be the sole guiding indicator when planning the decarbonization of an isolated research entity. Determining F_{sub} and β in the variety of situations encountered in experimental labs will presumably require tedious work. This will be key as part of any decarbonization planning.

3.3. Carbon tax

A carbon tax levied on TGS purchases and redistributed at the AR entity level would be modelled with the same equations as above (System 2) but changes in spending rate δS_t can be explicitly computed. To this end, we define γ the tax rate that applies on TGS. Because in our

simple framework there is only one type of targeted GS and thus only one value for F_t , γ is simply made proportional to the spending rate. We also define β the factor by which the expenditures of TGS are increased to the detriment of NTGS to offset some of the costs induced by the tax. Obviously, the amount of NTGS spending prior to mitigation S_{nt} places an upper limit on β : $\beta \leq \beta_{max} = (S_t + S_{nt})/S_t$. For completeness, we assume that part of the money κ gained from the tax and redistributed to the personnel ends up being used to buy TGS (which may or may not occur depending on the rules for redistribution).

The net change in TGS purchase rate writes:

$$\delta S_t P_1 = (\beta - 1)S_t P_1 - \gamma(S_t + \delta S_t)(1 - \kappa)P_1 \quad (8)$$

From this equation we deduce:

$$\delta S_t = -\frac{(1 - \kappa)\gamma - (\beta - 1)}{1 + \gamma(1 - \kappa)}S_t \quad (9)$$

Overall, the reallocation of the tax money to TGS purchase is equivalent to a reduction of the tax rate, although it may internally be associated with a redistribution among staff. In the rest of this subsection, we ignore this reallocation by redefining γ to incorporate the $1 - \kappa$ factor.

Fig. 4 illustrates the impact of a tax imposed on air travel. Obviously, a higher tax level results in a stronger reduction of the targeted emissions. For instance, a 50% reduction requires a tax level of about 600 €/tCO2e if there is no reallocation of money from NTGS to TGS, i.e. if β equals 1 (400 €/tCO2e when communicating vessels effect is ignored). Any reallocation reduces the effectiveness of the carbon tax. The goal of the tax is to reduce the emissions induced by TGS, hence to have a negative δS_t . Yet, the outcome can be very different in situations where β_{max} is significantly larger than $1 + \gamma$ (upper-left white sector in Fig. 4). This would generally be the case if the tax only affects air travel which, in general, represents a limited fraction of the research expenditures of typical AR entities. This is a major difference from a quota type restriction that has a direct control onto emissions (and S_t). Furthermore, in a real-world situation, scientists could seek additional sources of funding to compensate for the tax, rather than diverting spending from NTGS.

Carbon offsets are a variant of the carbon tax since their costs are generally proportional to the emissions offset. The difference is that 1) there is a net transfer of money outside of AR (adjustment term in Eq.

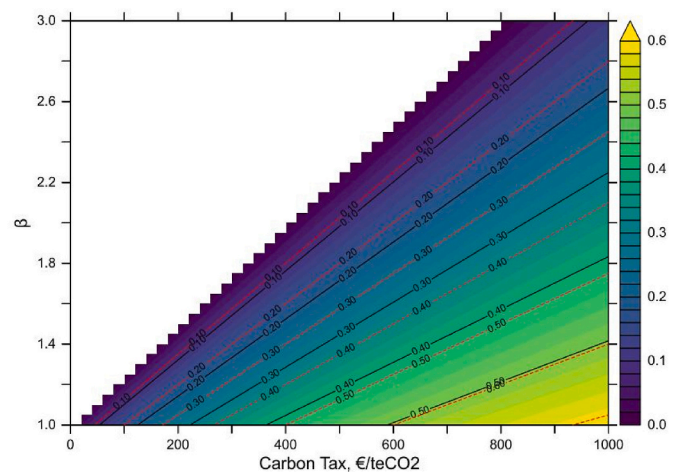


Fig. 4. Relative reduction of the targeted emissions with an imposed carbon tax. Shading and black contours include the emissions induced by reallocation of carbon tax to non targeted emissions. Red dashed contours is without taking into account this reallocation. In this figure, F_t and F_{nt} are set to 2.5 and 0.4 kgCO2e/€ respectively as shown in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(1a) which reduces the possibilities of communicating vessel effects within the AR perimeter but does not eliminate them; 2) If genuine emission reduction occurs elsewhere, they can be credited to the AR entity that purchased the offsets (negative adjustment term in Eq. (1c)).

4. Discussion: our model as a conceptual decarbonization framework

By formalizing the AR decarbonization in a stylized way, the objective of this study is to lay out a framework in which trade-offs between research budget (B), output (O), and CO₂ emissions (E) can become more familiar. We also hope that the mathematical formalism introduced in this study can provide a more neutral/transparent language to convey some value-loaded messages in an effective way, at least within the community familiar with this form of approach (as with the Kaya identity (Kaya, 1989; Jung et al., 2012)). The remainder of the discussion is written along this line.

4.1. Narratives for AR's transformation

Just as for most sectors of the society, AR's choices and decisions in the past decades have overwhelmingly been made based on B hard limits and O considerations largely oblivious to sustainability (Kern, 2011; Hottenrott and Lawson, 2013; Rosenbloom et al., 2015). Furthermore, similarly to most sectors of the society, integrating environmental footprint in its functioning turns out to be immensely difficult. In the academic world, two main contrasted narratives tend to oppose one another, not always explicitly and with various shades of gray between them.

A. The techno-scientific transition: science and innovation are the problem solvers; in this narrative AR aims to become climate neutral by accessing low-CO₂ resources (e-fuel premium when traveling, supercomputing centers with 100% renewable electricity supply, hydrogen or ammoniac-powered research vessels, high integrity carbon offsets to compensate residual emissions ...). Here, the transition is primarily envisioned through technological and scientific solutions that would provide goods and services with a low carbon (environmental) intensity (Lomborg, 2003), in line with sustainable development goal 9.4 (United Nations, 2015)). The expectation is that reaching carbon neutrality would have little to no effect on O, the nature and content of which can remain fundamentally unchanged (business-as-usual). Many past studies have investigated this scenario, particularly for economic growth (e.g., Weizsäcker et al., 1998; Lorek and Spangenberg, 2014; Scheer and Rubik, 2017). There are essentially two ways in which this can occur: i) if green premiums are small so that utility factors remain unchanged as the transition unfolds (green transition on affordable/widely available low-carbon commodities) or ii) if part or all of AR obtains preferential access (e.g. through additional budget) to pay for large green premiums (i.e., utility factors go down but $\delta B > 0$). The second case would imply a green transition of AR based on expensive/scarcely low-carbon commodities, meaning that societies agree to allocate a larger fraction of their GDP to this sector. In both cases, the trade-offs between footprint (E) and output (O), as reflected in Eq. (3) are lessened. And AR's environmental concern translates into ensuring that utility factors are as high as possible (efficiency).

B. The all-round ecological transformation: innovation is social and cultural in addition to techno-scientific; in this narrative, AR seeks to become climate neutral through an approach that is holistic in the sense that all terms in equations (1a)-(1c) are a priori considered as potential mitigation levers: utility (reuse, recycle, efficiency), carbon intensity, spending rates (including through restrictions), sufficiency, changes in workforce and in institutional norms that shape how output O is defined, e.g., what is considered good (or more emphatically "excellent") and useful research (Tijssen, 2003; Ferretti et al., 2018). Our study is mainly relevant to the transformation paths inspired by this narrative, as this is when the constraints and trade-off issues between B,

E and O are most acute.

By large, narrative A has presided over the destinies of academia's decarbonization (and more generally of the society). But narrative B is gaining ground as the environmental crisis unfolds and sufficiency is increasingly seen as part of the response (Bocken and Short, 2016). This is also reflected in the latest IPCC report, which emphasizes the importance and benefits of sufficiency. As a practical example of what narrative B looks like, a potential decarbonization strategy is now laid out for academia's air travel. We choose this example because air travel has a high emission factor (F), a relatively high spending rate in many AR entities, and also because the subjective perception of its usefulness has started to diminish in some circumstances (Quinton, 2020b; Glauzius, 2021).

1. Reduce air travel by 1/2 to 2/3 by 2030. Although larger reductions might be rapidly feasible in some fields and necessary in the subsequent decades, such a reduction can be seen as an ambitious initial target that nonetheless permits some long-distance travels essential to face-to-face scientific exchanges and field work. And it represents a substantial sufficiency step (involving reconsideration of O), and thus significant financial savings (leaving aside the possibility of a dramatic increase in fuel cost).
2. Further reduce CO₂ emissions by using these savings to pay for substitutions involving low-carbon goods and services. Alternative jet fuel for remainder of air travel is a prime candidate because it could supply substantial CO₂ reductions. In addition, airplane emissions of short-term climate forcing factors (such as contrails), excluding CO₂, could be compensated through the purchase of carbon offsets with high social and environmental value but lacking permanence, for instance from afforestation/reforestation programs (presumably at a price 10–15 \$ per ton of equivalent CO₂ Swinfield and Balmford, 2023). A 50–66% reduction of air travel could provide resource commensurate with the purchase of a combination of high integrity AJF (Fig. 1) and carbon offsets.

AR has played and is playing an important role in improving the production process of low-carbon liquid fuel, assessing their full environmental and social integrity, and engaging in public communication about identified issues (e.g., Gutiérrez-Antonio et al., 2017; Wise et al., 2017; Santos et al., 2018). The fact that AR partly relies on AJF for its decarbonization should arguably be accompanied by a responsibility to continue and strengthen these contributions (which will affect O). The same could apply to carbon offsets. This, the sufficiency effort (point 1 above) and obviously the utility of many contributions of AR to society are proposed as a tentative ethical framework to justify continued AR air travel despite its detrimental environmental and social impacts. Such an approach would be qualitatively consistent with recent AR6 messages about the need to combine sufficiency and innovation, in order to ensure equitable access to low-carbon resources while limiting the social-/environmental impacts inherent to their production [AR6, IPBES/IPCC] (see also Humpenöder et al., 2018; Prudhomme et al., 2020).

4.2. Research output and the transformation of academia

The framework presented here has been developed to explore the decarbonization of a small or medium-sized research entity. As illustrated here, several policies can be instigated such as the capping of the emissions induced by some targeted activities, the implementation of a carbon tax, or the substitution of certain laboratory equipment or consumables. Trading of emissions with external entities is included in our framework (E_{ex} in Eq. (1c)), even if its effects have not been explored here. In that case, it shares some similarities with the cap-and-trade regulation (Perdan and Azapagic, 2011; Schmalensee and Stavins, 2017). From a mathematical perspective, adding one system constraint (on the environmental footprint E) while keeping the budget constraint B unchanged shall a priori yield a different "optimal" output O. Such

problems of optimization with joint constraints have been studied for other sectors of activity (e.g., Du et al., 2016; Zhou et al., 2016; Turki et al., 2018; Jin et al., 2020). However, in the case of academic research, this formal approach and our model have little to offer about O adjustments because no equations exist to represent the social, psychological, and institutional processes that influence how O is subjectively defined and can evolve with time.

The evaluation of O (and of the associated utility factors) is based on theories about the utility of scientific knowledge production (Hessels and van Lente, 2008; Molas-Gallart and Rafols, 2018). In recent past decades, there has been increasing political concern and demand for defining methodologies to evaluate the quality and efficiency of science, not least because research has increasingly been seen as a provision of actual services and economic outputs (Gibbons et al., 1994; Etzkowitz and Leydesdorff, 1998). In many countries, national research evaluation systems or procedures have been developed at the individual, laboratory and/or institutional levels (Whitley and Glaeser, 2007; Ochsner et al., 2018). Many of these systems rely, at least in part, on quantitative indicators based on bibliometric and scientometric methods. However, O and utility factors are intrinsically linked to qualitative value judgments that are, to some extent, formed within academia itself (Chavarro, 2020). As a limit case, rare voices among scientists have suggested that in some areas, research is useless (Utility Factors are null) and/or should be paused (O should vanish) (Ioannidis, 2016; Glavovic et al., 2022; Carrey et al., 2019).

Less radical evolutions involve making E considerations an integral part of the definition of O so as to reduce their degree of antagonism. This is frequently expressed in relation to society-wide CO₂ emission or more general environmental damages which research is called to help alleviate (Park and Mrsny, 2021; Dwivedi et al., 2022; Heard et al., 2022, see also the editorial of Nature volume 601, 6 Jan. 2022). But reshaping O can also mean achieving footprint reductions in the AR sector itself. A case in point in some countries concerns the evolution of the criteria considered in AR recruitment juries and career evaluation procedures with, for instance, less emphasis being placed on attendance to international conferences. These is just one among many ways through which the definition of O could be reshaped from within the academia. But, like other professional sectors, AR is not isolated and its transformation will obviously also depend on changes in other areas of society (Bernstein and Hoffmann, 2019).

5. Conclusion

Faced with the necessity to decarbonize academic research, initiatives have started to be implemented on the scale of research entities with 10–1000 personnel (project consortia, laboratories, institutes ...) that are most frequently partial in scope (as opposed to, e.g., a global carbon tax) (da Silva et al., 2023). In this study, we propose an idealized model that sheds light on the difficulties of a partial/incremental transformation process characterized by the integration of environmental constraints through decarbonization measures of limited scope.

One of our key assumptions is that the modelled entity has a fixed budget but controls reallocations between expenditure items. Although the latter may, at present time, not be systematically satisfied, it is hoped that fungibility-related barriers to transformation will be lifted as the urgency of ecological transformation is increasingly recognized. More fundamentally, competition for high-integrity goods and services is likely to increase as governments adopt more ambitious policies to reduce greenhouse gas emissions and improve environmental preservation. The resulting increase in the cost and scarcity of these goods and services makes the question of "who pays for decarbonation of academia?" an ethical one. Lacking visibility on so many aspects of the ecological transformation, having AR undertake a sufficiency effort to free up the financial resources needed to pay for premiums on low-carbon goods and services (see Sec. 4.1) seems a socially interesting and pragmatic approach overall, hence our assumption of a fixed

budget.

Major challenges to decarbonization conducted in this framework are the communicating vessel effects whereby efforts aimed at reducing the purchase of specific goods or services are counteracted by an increase in the purchase of others. Conversely, certain beneficial communicating vessel effects can be generated whenever a particular transformation leads to saving money, which can subsequently be spent on additional decarbonization efforts. Anticipating, monitoring, and controlling moving vessel effects appear to be essential. The scale at which decarbonization is being conducted must have an influence on the ability and opportunities to optimize these effects and the underlying redistributive budget transfers among AR personnel. We offer several case studies and guidelines relevant to a variety of practical situations encountered in academia and elsewhere. Generally speaking, the elements targeted by decarbonization should not be chosen solely because of their elevated contribution to emissions (i.e. how high $S_t F_t$ is) or the cost of an avoided ton of CO₂. They must be chosen for an ensemble of reasons also involving the CO₂ intensity of the anticipated substitutions (precisely $F_t - F_{nt}$), the potential magnitude of δS_b , as well as indirect effects on how research output is defined and perceived. Although feasibility and benefits need to be estimated on a case-by-case basis, hiring support staff as part of AR transformation should a priori be favored thanks to their low associated emission intensity. Air transport will be a key lever for some research entities, but measures targeting the other emission sources will be essential. Follow-up studies with toy models of the type we develop in this work will be useful to conduct as key figures feeding model parameters become better ascertained.

Finally, capping GHG emissions from academic research can be seen as equivalent to considering these emissions as a limited resource, as is the case with money. In the mathematical framework we have developed here, this amounts to steering research with two budgets: a carbon budget and a monetary budget. This implies that optimal knowledge production will change and/or that the definition of optimal knowledge production should be redefined, and include for example (but not only) environmental indicators.

CRediT authorship contribution statement

Xavier Capet: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Olivier Aumont:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xavier Capet reports financial support was provided by National Centre for Scientific Research (CNRS). Olivier Aumont reports financial support was provided by Institut de Recherche pour le Développement (IRD).

Data availability

The data used in the study is simple enough to be provided in the manuscript (eg. table 1)

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