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Is Decarbonization Achievable ?
Essays on the Economics of the Energy Transition

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1. *Ecological Economics*, 2019.

2. Joint with Mouez Fodha & Francesco Ricci, *Resource and Energy Economics*, 2020.
3. Joint with Mohammed Bachir & Sebastián Tapia García.
4. Joint with Thomas Douenne, in second revision in *American Economic Journal: Economic Policy*.
5. Joint with Thomas Douenne, *Ecological Economics*, 2020a.

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6. Fabre & Wagner (2020)
7. Bastidas et al. (2019)
8. Y compris des travaux qui ne font pas partie de cette thèse (Fabre, 2016, 2017, 2018, n.d.).

approximatif.

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9. Outre les nombreux oublis, un intrus s'est glissé dans cette liste. Saurez-vous le débusquer ?

Préambule

Comprendre le changement climatique

La rapide croissance de la population et de la consommation qui a cours depuis la révolution industrielle est entretenue par la combustion d'hydrocarbures fossiles (charbon, pétrole, gaz), qui délivrent 85% de l'énergie primaire utilisée dans le monde (BP, 2019). Le principal produit de cette combustion est le dioxyde de carbone (CO_2) : sa concentration dans l'atmosphère est ainsi passée de 280 particules par million (ppm) avant la révolution industrielle à 415 ppm en 2020 (Meinshausen et al., 2017). Le CO_2 est un gaz à effet de serre : il absorbe le rayonnement infrarouge de la Terre et en convertit l'énergie électromagnétique en énergie thermique, piégeant au passage cette énergie dans l'atmosphère sous forme de chaleur. Si environ la moitié des émissions de CO_2 est absorbée au bout d'un siècle par la biosphère (à travers la croissance des plantes par photosynthèse) ou par l'hydrosphère (à travers la dissolution de CO_2 dans l'océan jusqu'à l'équilibre thermodynamique), 10 à 20% d'entre elles reste dans l'atmosphère durant des milliers d'années, altérant durablement le climat (Archer et al., 2009; Jones et al., 2013; Millar et al., 2017). De façon remarquable, l'anomalie de température par rapport à la période pré-industrielle est bien approximée par la quantité cumulée d'émissions anthropiques de gaz à effet de serre (Allen et al., 2009; Matthews et al., 2009). Ainsi, seule la *neutralité carbone* (c'est-à-dire l'arrêt de ces émissions ou leur compensation par une extraction du CO_2 atmosphérique) mettrait fin au changement climatique induit par l'altération de la composition atmosphérique, tandis qu'il faudrait revenir à une concentration de 350 ppm par une extraction nette de CO_2 pour que le climat se stabilise autour des conditions climatiques actuelles (Hansen et al., 2013).

Si, au contraire, les émissions de gaz à effet de serre continuent de croître suivant la tendance passée jusqu'en 2100 et décroissent ensuite linéairement jusqu'à 0 en 2300, alors la concentration en CO_2 atteindrait 1000 ppm en 2100, 2000 ppm en 2300, et l'anomalie de température serait de +4°C en 2100, et jusqu'à +7-8°C entre 2300 et 5000 (Montenegro et al., 2007). La Terre atteindrait alors des températures inégalées depuis 20 millions d'années (Zachos et al., 2008). Dans un scénario d'émissions similaire (le scénario RCP 8.5 du GIEC [10]), la fonte de l'inlandsis Ouest-Antarctique pourrait élever le niveau de la mer de 15 mètres d'ici 2500 (DeConto & Pollard, 2016) et submerger d'ici 2300 des zones côtières où vivent actuellement 950 millions de personnes (Kopp et al., 2017). Dans un scénario plus extrême, où encore plus d'hydrocarbures fossiles seraient brûlées, l'anomalie de température pourrait atteindre +16°C, rendant la majorité des terres inhabitable pour les mammifères (de telles températures causant une hyperthermie létale) (Hansen et al., 2013). Même dans

10. Plus précisément, le Groupe International d'Experts sur le Climat (GIEC) a défini quatre trajectoires de référence pour les concentrations de gaz à effet de serre, les Representative Concentration Pathways (RCP), désignés par leur forçage radiatif en l'an 2100 (8.5 W/m^2 pour le RCP 8.5, IPCC, 2013).

le scénario RCP 8.5, de vastes zones de Chine, d'Asie du Sud et du Moyen-Orient seraient rendues inhabitables au XXII^e siècle du fait d'une température du bulbe mouillé excédent régulièrement la valeur létale de 35°C (ce qui n'arrive nulle part sous le climat actuel) (Pal & Eltahir, 2016; Im et al., 2017; Kang & Eltahir, 2018). Dans un scénario d'émissions moins extrême (le scénario RCP 4.5), avec une température de +2°C en 2100 et +2.5°C en 2300, la température correspondrait à celle de la dernière période interglaciaire (il y a 125 000 ans) (Snyder, 2016) où le niveau de la mer était 6 à 9 mètres plus élevé qu'aujourd'hui, principalement à cause de la fonte des pôles (Turney et al., 2020). Dans ce scénario, on peut s'attendre à une hausse du niveau de la mer semblable à terme, celui-ci étant principalement dû à la température. Mais même si ce nouvel équilibre ne serait pas atteint avant plusieurs centaines d'années, dès 2100 le niveau de la mer submergerait (en l'absence de digues) des zones où vivent actuellement 250 millions de personnes (Kulp & Strauss, 2019), et où une forte croissance de la population est anticipée (Neumann et al., 2015). Du fait de la montée des eaux, des villes entières devront être déplacées lorsque les protections sous forme de digues se révéleront impossibles ou trop coûteuses à construire (Hinkel et al., 2014; Diaz & Moore, 2017). De manière générale, nos infrastructures (et nos usages des sols) sont adaptées au climat actuel et le changement climatique en rendra de nombreuses obsolètes, lorsqu'elles ne seront pas tout simplement détruites (CCR, 2018). Sous l'effet du changement climatiques, la disponibilité en eau douce (par les précipitations et les cours d'eau) devrait s'accroître dans certaines régions (Europe, Asie du Sud-Est, côte Est des États-Unis) mais elle baisserait dans d'autres, dont les plus peuplées (Chine, Asie du Sud), multipliant les périodes de sécheresse et aggravant le stress hydrique (Elliott et al., 2014). Aussi, Schlenker & Lobell (2010) estiment qu'en l'absence de mesures d'adaptation, le changement climatique entraînera d'ici le milieu du siècle une baisse de rendements agricoles d'environ 20% pour les principales cultures d'Afrique sub-saharienne. Un réchauffement de 2 ou 3°C, lui, entraînerait des baisses de rendements agricoles face auxquelles même les mesures d'adaptation seraient inefficaces (Moore et al., 2017). Aussi, dès l'an 2000, 166 000 morts étaient imputables annuellement au changement climatique, principalement à cause de ses conséquences en termes de malnutrition, diarrhée et malaria en Afrique et en Asie du Sud (Patz et al., 2005). Et cela sans compter les 6 millions de morts annuels dues à la pollution de l'air engendrée par les énergies fossiles (Gakidou et. al, 2017). Par ailleurs, les températures élevées sont associées à une productivité plus faible face à laquelle l'adaptation semble impossible (Burke & Tanutama, 2019), notamment pour les activités de plein air (Behrer et al., 2019). Pour résumer, la continuation des émissions de gaz à effet de serre mettrait en péril de multiples pans de la société (Dell et al., 2012; Carleton & Hsiang, 2016), accroissant la probabilité de conflit violent (Burke et al., 2009), et entraînant d'importants déplacements de population (Cattaneo et al., 2019).

Dépasser l'âge des hydrocarbures fossiles

Si nous poursuivons sur le long terme des activités émettrices de gaz à effet de serre telle que l'exploitation des hydrocarbures fossiles, la seule façon de contenir la hausse de la concentration atmosphérique en CO_2 est son extraction depuis l'atmosphère [11]. La reforestation ainsi qu'un meilleur

11. La hausse moyenne de la température pourrait certes être évitée malgré une hausse de la concentration en CO_2, grâce à des techniques d'ingénierie climatique telles que l'injection d'aérosols sulfatés dans la stratosphère (ces gaz étant connus pour assombrir et donc refroidir la planète). Cependant, tous les spécialistes conviennent qu'il ne faut pas substituer une telle démarche à la décarbonation, car elle présente de sérieux problèmes : effondrement des précipitations, acidification des océans, réchauffement climatique exacerbé en cas d'interruption de l'injection, etc. (Robock et al., 2009).

usage des sols sont les solutions privilégiées pour accomplir cette extraction, mais leur potentiel est limité et sera vite saturé, même dans les scénarios les plus volontaristes (Griscom et al., 2017). Dans le cas de la reforestation, le captage du CO_2 est obtenu naturellement par la photosynthèse à l'origine de la croissance des plantes. [12] Sa séquestration repose généralement sur la préservation de la biomasse nouvellement créée, bien qu'une plus grande utilisation de bois de construction permettrait aussi de stocker du carbone. Il a également été proposé de couper et enterrer du bois (Scholz & Hasse, 2008), mais cela requerrait de convertir une grande partie des forêts mondiales à cet usage (Köhl & Frühwald, 2009). Une autre solution d'extraction consiste à utiliser la biomasse comme combustible dans des centrales thermiques produisant chaleur et électricité, le CO_2 des cheminées pouvant ensuite être capté et séquestré artificiellement. L'intérêt de cette solution varie selon chaque projet : certains projets valorisent des déchets agricoles et affichent un bon rendement, mais d'autres empiètent sur des terres agricoles ou ont une empreinte carbone trop élevée par rapport au CO_2 extrait (et parfois même supérieure, European Academies Science Advisory Council, 2019). Outre les centrales à biomasse, le captage peut s'effectuer dans les cheminées de n'importe quelle usine qui brûle du combustible, ce qui permet de réduire notablement les émissions d'une centrale électrique thermique par exemple (IEA, 2016). La séquestration artificielle s'effectue actuellement dans des cavités géologiques étanches, notamment d'anciens puits de pétrole (IPCC, 2005). Le captage depuis les cheminées et la séquestration sont déjà déployées à l'échelle industrielle car elles servent à la récupération assistée du pétrole : les injections de CO_2 permettent de rétablir une pression suffisante pour pomper le pétrole restant dans les puits proches de l'épuisement (pétrole qui, une fois brûlé, émet l'équivalent d'au moins la moitié du CO_2 injecté pour l'extraire, Mac Dowell et al., 2017). Le captage direct de CO_2 depuis l'air est également possible, mais n'existe pour l'instant qu'à l'échelle de prototypes à travers une dizaine de projets expérimentaux (Ishimoto et al., 2017), et requiert autant d'énergie qu'il en a été délivrée par la combustion des hydrocarbures à l'origine du CO_2 capté (Ranjan & Herzog, 2011).

Ces solutions sont coûteuses, n'ont pas toutes atteint le stade de maturité industrielle, et reposent *a priori* sur les capacités géologiques de stockage du CO_2. Les estimations de ces capacités sont peu fiables, mais elles correspondent à entre 50 et 400 ans d'émissions actuelles (IPCC, 2005). Il est donc peu probable que les capacités soient suffisantes pour stocker le CO_2 qui serait émis si toutes les ressources d'hydrocarbures fossiles étaient brûlées, celles-ci correspondant à au moins 1000 ans d'émissions actuelles (principalement sous forme de charbon) (Johansson et al., 2012). De plus, aussi importantes les ressources fossiles soient-elles, elles sont finies, et seront épuisées au bout de quelques milliers d'années si leur consommation continue au rythme actuel. Il est probable que les humains vivront encore plusieurs dizaines de milliers d'années, si ce n'est plusieurs millions d'années. Dans ce cas, cela signifie que nos descendants connaîtront un jour un système énergétique ne reposant pas sur les hydrocarbures fossiles. Que les hydrocarbures fossiles viennent à manquer ou que leur usage pose plus de problèmes qu'il n'en résout, s'ouvre donc la perspective

12. Il a un temps été envisagé de fertiliser les océans par des injections de fer ou d'autres nutriments (phosphore, azote) car ce sont les facteurs limitants de la croissance du phytoplancton (Coale et al., 1996). En effet, lors d'un processus biochimique appelé la « pompe biologique », une partie du CO_2 absorbé par le phytoplancton lors de photosynthèse se dépose sur le plancher océanique sous la forme de carbonate de calcium : il y est alors séquestré dans les sédiments pendant des millions d'années. Cependant, les effets de la fertilisation des océans sont incertains et potentiellement néfastes ou contre-productifs, celle-ci pouvant induire des zones mortes par eutrophisation qui dégageraient du méthane et d'autres gaz à l'effet de serre plus puissants que le CO_2 séquestré (Chisholm et al., 2001; Lampitt et al., 2008). Aussi, plusieurs scientifiques ont appelé à abandonner cette idée, car pour qu'une expérience permette de bien mesurer tant le potentiel de séquestration du CO_2 que les effets secondaires de la fertilisation, celle-ci devrait être menée à grande échelle sur une centaine d'années, et elle mettrait alors en péril les écosystèmes marins (Strong et al., 2009).

d'une civilisation industrielle décarbonée. Ainsi, il est légitime de s'interroger sur la possibilité d'un système énergétique durable reposant uniquement sur des sources d'énergie renouvelables maîtrisées, au vu de la finitude des ressources en uranium et plutonium (qui sont du même ordre de grandeur que les fossiles si la surgénération est employée, Johansson et al. 2012) et du fait que le déploiement industriel d'autres technologies nucléaires (thorium, fusion) est loin d'être acquis.

Choisir le niveau d'ambition climatique

Pour décider de décarboner ou non le métabolisme industriel, il faut savoir quelle valeur nous attribuons à un système énergétique décarboné et à un climat stabilisé d'une part, et la comparer à la valeur du confort apporté par les énergies fossiles d'autre part. Puis, dans la mesure où nous décidons de décarboner le système énergétique, il est nécessaire de fixer la vitesse et l'ampleur avec lequel nous le faisons, en attribuant une valeur aux climats possibles dans chaque scénario d'émissions, et en la comparant aux efforts impliqués par la transformation plus ou moins rapide et profonde de nos modes de vie requise par chaque scénario. Cet arbitrage est compliqué par le fait qu'il implique la comparaison de situations incertaines et à différentes époques, mais surtout la comparaison de son bien-être vis-à-vis du bien-être d'autrui. Du point de vue d'un planificateur impartial, cet arbitrage se fonde nécessairement sur des règles éthiques qui permettent de comparer le bien-être de différentes générations ainsi que de populations qui diffèrent par leur revenu, leur dépendance aux énergies fossiles et leur vulnérabilité au changement climatique (elle-même combinaison de l'exposition à ses impacts et de la capacité d'adaptation, très liée à la richesse). La méthode privilégiée par les économistes pour assembler toutes ces considérations et calculer la décision optimale est la modélisation intégrée de l'économie et du climat. De nombreux modèles ont été proposés, qui diffèrent par leurs choix de modélisation mais sont tous constitués de quatre éléments fondamentaux.

Premièrement, la fonction de bien-être social décrit l'objectif à optimiser et intègre des considérations aussi bien éthiques que pragmatiques. Même s'il est reconnu qu'éthiquement, aucune population ne devrait être privilégiée sur une autre (Ramsey, 1928; Gollier, 2017) ; en pratique, les décideurs privilégient souvent leurs compatriotes sur les étrangers et leur génération sur les suivantes. Certains auteurs adoptent malgré tout une démarche éthique : ils accordent le même poids à chaque humain d'une même génération, et ne déprécient la valeur d'une génération que dans la mesure où son existence est rendue incertaine pour des raisons exogènes (à cause d'une extinction météoritique par exemple) (Chichilnisky, 1996; Stern et al., 2007). En revanche, d'autres auteurs préfèrent formuler des recommandations en conformité avec le niveau limité d'altruisme supposé des décideurs (Nordhaus & Sztorc, 2013; Rezai & Van der Ploeg, 2016; Dietz & Venmans, 2019) : ils accordent un poids inférieur au bien-être des populations les moins influentes, en dépréciant substantiellement chaque génération par rapport à la précédente, et en figeant les différences de revenu entre pays (Stanton, 2011) [13] (ce qui contredit l'implication éthique de redistribution découlant de l'hypothèse usuelle que le bien-être individuel dépend uniquement du revenu). Par ailleurs,

13. Comme l'écrit Stanton (2011) : « Les modélisateurs ont considéré la tendance à l'égalisation des revenus entre les régions comme un problème, dont la solution consiste à contraindre le modèle à considérer l'utilité marginale du revenu comme étant la même dans toutes les régions (sur une période donnée). Un ensemble de "poids de Negishi" est inclus dans les fonctions d'utilité régionale, de sorte que la contribution pondérée au bien-être social d'un dollar de consommation supplémentaire est la même dans toutes les régions. Des pondérations plus élevées sont attribuées au bien-être dans les pays riches, tandis que le bien-être dans les pays pauvres reçoit des pondérations plus faibles. Cette procédure permet d'éviter l'égalisation des revenus dans les modèles intégrés. »

la fonction de bien-être social incorpore d'autres choix éthiques épineux, tels que l'aversion à l'inégalité (Fleurbaey & Zuber, 2012; Anthoff & Emmerling, 2019), l'aversion au risque (Weitzman, 2009; Heal & Millner, 2013; Jensen & Traeger, 2014), ou la préférence relative entre la taille de la population et son niveau de bien-être (Scovronick et al., 2017). Deuxièmement, des hypothèses sur les dynamiques du climat et de l'économie permettent d'estimer le climat futur en fonction de la trajectoire des émissions de gaz à effet de serre et d'autres activités humaines agissant sur le climat, et d'établir un scénario crédible concernant l'évolution du progrès organisationnel et technique ainsi que des comportements sociaux (en termes d'épargne, de fécondité, etc.). Les modèles présentent parfois un caractère stochastique pour rendre compte des connaissances limitées sur ces dynamiques. Troisièmement, les modèles comprennent une fonction de dommages, qui évalue les dégâts lié au changement climatique pour chaque climat possible, souvent résumé par l'anomalie de température globale et parfois aussi par le niveau des océans. Cette fonction de dommages agrège généralement les dommages sur le capital, la production, la santé, et la biodiversité, et les convertit en perte de revenus (Moore & Diaz, 2015; Howard & Sterner, 2017). Quatrièmement, les modèles incluent une courbe du coût marginal d'abattement, qui lie chaque réduction additionnelle d'émissions de gaz à effet de serre à son coût. Ainsi, de tels modèles sont agnostiques sur les technologies de réduction d'émissions à mettre en œuvre, car ils supposent que le choix de ces technologies dépend uniquement de leur coût, ou du moins que les seuls paramètres pertinents pour la décision sont la réduction d'émissions et son coût (qui réduit d'autant la consommation et donc le bien-être) (Enkvist et al., 2007; Kesicki, 2011). Cette convertibilité entre les différents dégâts et les différentes formes de réduction d'émissions en une même notion de coût permet d'arbitrer entre l'ampleur des dégâts et l'effort de réduction d'émissions. En effet, le niveau d'effort optimal est défini comme celui pour lequel le planificateur est indifférent entre fournir ou non un effort additionnel de réduction d'émissions, le coût en termes de dégâts ainsi évités étant alors égal au coût d'abattement additionnel correspondant. Ce coût est généralement croissant dans le temps et est dénommé « coût social du carbone », car il correspond à un coût (en termes de dégâts ou d'abattement) qui n'est pas subi spécifiquement par l'émetteur des émissions (contrairement au coût du combustible), mais qui se répartit sur l'ensemble de la société. Certains modèles simples donnent une expression analytique pour la trajectoire optimale du coût social du carbone (Golosov et al., 2014; Traeger, 2015; Rezai & Van der Ploeg, 2016; van den Bijgaart et al., 2016; Dietz & Venmans, 2019), tandis que des modèles plus sophistiqués calculent numériquement la trajectoire qui maximise la fonction de bien-être social (Bosetti et al., 2006; Hourcade et al., 2010; Hope, 2011; Stehfest, Elke et al., 2014; Anthoff & Tol, 2014; Nikas et al., 2019).

Prévoir la transformation du système de production

Une approche alternative, qui découle du fonctionnement des négociations climatiques et des traités internationaux (Kyoto, Paris), consiste à procéder en deux temps. Dans un premier temps, un objectif climatique est décidé, souvent exprimé en termes d'anomalie de température, et sa valeur est guidée aussi bien par des résultats de modèles intégrés que par des considérations plus élémentaires sur ce qui constitue la limite d'un changement climatique acceptable. Dans un second temps, cet objectif est intégré comme contrainte dans les modèles intégrés et y rend obsolète la fonction de dommages. Chaque modèle donne alors une trajectoire de coût des émissions de gaz à effet de serre qui permet de respecter l'objectif climatique tout en assurant une répartition optimale des efforts d'abattement dans le temps. Le coût des émissions s'appelle dans ce cas la « valeur de l'action pour le climat » (Quinet, 2019) car elle représente la valeur que nous accordons au futur et à autrui à travers la transformation de nos modes de vie qui permet d'atteindre notre climat objectif. Cette valeur de l'action pour le climat s'appelle encore le « prix fictif » des émissions, car dans un marché sans défaillance et d'après le principe « pollueur–payeur », il représente le prix des émissions qui permet de réaliser la trajectoire d'émissions indiquée par le modèle. En effet, dans la mesure où les émissions de gaz à effet de serre deviennent payantes, les agents économiques vont réduire leurs émissions, soit par simple contrainte budgétaire, soit par la substitution de leurs activités polluantes par d'autres activités rendues comparativement moins chères. La courbe des coûts marginaux d'abattement est alors l'élément-clé qui permet de déterminer la valeur de l'action pour le climat, car elle donne le prix des émissions requis pour effectuer chaque degré d'abattement. L'observation de cette courbe nous enseigne que parmi les abattements les moins chers, il y a la décarbonation du mix électrique. En effet, obliger les centrales à charbon à payer 30€ pour chaque tonne de CO_2 qu'elles émettent suffirait à rendre l'électricité d'origine renouvelable compétitive par rapport à celle des vieilles centrales à charbon [14], qui est souvent encore la moins chère (Kesicki & Ekins, 2012). Dans certains cas qui dépendent des spécificités locales, des centrales à charbon pourraient rester compétitives malgré un prix élevé sur les émissions, en captant et séquestrant le CO_2 de leur cheminées : ce serait le cas uniquement lorsque ce captage et séquestration coûteraient moins chers que les émissions évitées, et lorsque le surcoût qu'elles induiraient resterait en-deça du surcoût de l'électricité d'origine renouvelable. Cependant, dans tous les cas, un niveau suffisamment élevé de prix sur les émissions permettrait de décarboner le mix électrique. De même, avec un prix des émissions encore plus élevé, entre 100 et 500 €/tCO_2, les voitures électriques deviendraient compétitives par rapport aux voitures thermiques (même sans aide de l'État), et l'isolation des bâtiments deviendrait véritablement rentable (Quinet, 2019). En revanche, la neutralité carbone semble très difficile pour certains secteurs semblent dont les émissions ne sont pas uniquement dues à l'usage d'énergie fossile : c'est le cas de l'agriculture, de la production de ciment ou encore d'acier. Pour compenser les émissions de ces secteurs, il faudra sans doute employer une « technologie ultime » (*backstop technology*), permettant d'extraire le CO_2 atmosphérique. Le prix d'une telle technologie correspondra alors à la valeur de long terme de l'action pour le climat, lorsque nous aurons décidé de compenser chaque émission anthropique de gaz à effet de serre par une extraction correspondante depuis l'atmosphère. En effet, si un agent doit payer pour ajouter du CO_2 dans l'atmosphère, il est logique qu'un agent qui en enlève de façon pérenne soit rétribué d'un montant équivalent. Les technologies de captage direct du CO_2 de l'air [15] évoquées plus haut sont presque des technologies ultimes, et pourraient devenir rentables à partir de 200 €/tCO_2 voire 20 €/tCO_2 selon des ingénieurs de cette industrie naissante (Ishimoto et al., 2017; Keith et al., 2018; Breyer et al., 2019; Fasihi et al., 2019), mais pas en-dessous de 1000 €/tCO_2 selon des universitaires sceptiques (Ranjan & Herzog, 2011; House et al., 2011). Ces technologies ne sont toutefois pas tout à fait « ultimes » car elles reposent sur des capacités de stockage limitées : elles n'offrent donc une solution que pour les prochains siècles, mais pas pour le très long terme. Aussi, une solution technologique véritablement ultime, mais vraisemblablement plus coûteuse, consisterait à convertir le CO_2 sous une forme solide ou liquide (et non gazeuse) chimiquement stable, telle que le carbonate de calcium ($CaCO_3$) ou des hydrocarbures obtenus par photosynthèse artificielle. Cela dit, comme les recherches sur de tels procédés n'en sont qu'à leurs débuts, il est encore trop

14. Ce chiffre est une moyenne mondiale. En Europe, c'est plutôt autour de 100 €/tCO_2 que l'électricité d'origine renouvelable serait compétitive par rapport à celle des centrales thermiques (RTE, 2016).

15. À ne pas confondre avec le captage du CO_2 depuis les cheminées d'usine.

tôt pour pouvoir estimer le coût d'une technologie véritablement ultime (Ma et al., 2009; Li et al., 2014).

Une fois fixées les trajectoires des émissions et de leur prix, d'autres modèles sont employés pour détailler les investissements à mener dans un secteur précis. Par exemple, un modèle d'ingénieurs de type « bottom-up » peut être utilisé pour optimiser le système de production d'électricité à l'échelle d'un continent comme l'Europe. Le modèle prend en compte les centrales existantes, leur durée de vie, les potentiels de production heure par heure en chaque point du continent, et détermine les investissements à effectuer pour satisfaire au moindre coût un scénario de demande, éventuellement sous la contrainte que certaines technologies soient mises de côté. À l'aide d'un tel modèle, l'Agence Internationale de l'Énergie a ainsi calculé l'évolution optimale des systèmes énergétiques de chaque région du monde d'ici 2050, selon différents scénarios d'émissions (IEA, 2010). De même, dans le cadre d'un rapport commandé par Greenpeace (Teske et al., 2015), une équipe de chercheurs a calculé le système énergétique optimal sous la contrainte que toute l'énergie mondiale provienne de sources renouvelables d'ici 2050. Ce rapport n'est pas un travail isolé : d'autres travaux ont montré comment il était possible de décarboner complètement et rapidement notre économie (García-Olivares et al., 2012; Jacobson et al., 2017; Scholz et al., 2017). Un point commun entre tous ces exercices prospectifs est la diversité des technologies employées : il n'y a pas une technologie miracle qui deviendrait hégémonique, au contraire le système optimal se compose de la plupart des technologies décarbonées connues. Cela est dû à la diversité des usages, à la diversité des potentiels suivant les régions, et aux coûts unitaires d'une technologie généralement croissants quand sa part dans le mix devient importante.

Faire payer les émissions

Une fois qu'a été décidée l'envergure des réductions d'émissions et évaluées les implications concrètes en termes de transformation du système de production, il reste à déterminer le meilleur agencement de politiques publiques pour réaliser la transition. Dans une société avec une juste répartition des richesses dotée d'un marché sans autre défaillance que l'absence d'un prix sur les émissions de gaz à effet de serre, la mesure optimale consiste à imposer un même prix sur toutes les émissions de gaz à effet de serre, égal au coût social du carbone (Pigou, 1920). Plutôt que de privilégier certaines méthodes d'abattement particulières, un prix uniforme sur les émissions garantit que l'abattement se fait au moindre coût, car les abattements mis en œuvre sont exactement ceux coûtant moins chers que le prix de l'émission évitée. C'est la rationalité supposée des agents qui assure qu'aucun coût d'abattement ne sera dilapidé et que tous les abattements rentables seront entrepris. Le prix sur les émissions peut être révisé régulièrement à mesure qu'on affine nos estimations des paramètres qui permettent de le calculer (les coûts d'abattement, la dynamique climatique, les dégâts du changement climatique...) ou à cause d'une évolution de nos préférences (altruisme pour les générations futures, aversion au risque). Ce prix peut provenir d'une taxe, d'un marché de permis d'émissions mis aux enchères par la collectivité dans la limite d'un quota global, ou d'une combinaison des deux (un marché de permis doté d'un prix plancher et d'un prix plafond par exemple), et c'est cette dernière solution qui est optimale (Weitzman, 1974; Pizer, 2002). Cependant, si le montant de la taxe ou le quota global d'émissions est révisé régulièrement, les différences entre taxe et marché de permis s'estompent. Le seul paramètre qui reste décisif est le niveau du prix (ou du quota) : celui-ci pourrait être déterminé par la médiane des votes d'une assemblée mondiale afin d'assurer le principe démocratique « une personne : une voix » (Weitzman, 2017).

Loin de cette économie stylisée fictive, la société actuelle requiert de mettre en œuvre une panoplie de mesures pour lutter contre le changement climatique. Si un prix sur les émissions fournit un repère utile par rapport auquel évaluer d'autres politiques publiques (et en particulier leur coût d'abattement), se reposer uniquement sur un prix ne peut constituer la solution optimale pour plusieurs raisons. La principale raison tient aux grandes disparités de revenus, de patrimoine, et de dépendance aux énergies fossiles. En effet, la taxe carbone [16] entraîne de larges effets distributifs, qui aggravent souvent les inégalités. Comme (en moyenne) la part des revenus consacrée aux dépenses de combustibles décroît avec le revenu, une taxe carbone tend à aggraver les inégalités de pouvoir d'achat (Williams et al., 2015). Cet effet distributif peut d'ailleurs expliquer que des décisions d'augmenter les prix des carburants aient déclenché le mouvement des Gilets jaunes en France ainsi que des manifestations massives en Équateur et en Iran. Ce caractère régressif de la taxe carbone peut toutefois être corrigé pour peu qu'on utilise les recettes qu'elle engendre d'une façon redistributive (ce qui ne fut pas le cas dans les trois exemples pré-cités).

Redistribuer mensuellement les recettes d'une taxe carbone mondiale à part égale à chaque humain serait équivalent à attribuer à chaque humain un même permis d'émission échangeable, ce qui est assez élégant d'un point de vue normatif. Ainsi, ceux qui sont responsables de plus d'émissions que la moyenne perdraient davantage de pouvoir d'achat à cause des hausses de prix qu'ils n'en gagneraient suite à la redistribution des recettes, et vice versa. Une telle redistribution rendrait cette « taxe carbone avec dividende » progressive et permettrait de corriger en partie les inégalités de revenus actuelles. Cela dit, la division du monde en nations et le format intergouvernemental des négociations climatiques favorisent les positions nationalistes et contrarient les plans impliquant des transferts de richesse entre pays. Aussi, de nombreux commentateurs se résignent à proposer la mise en place d'une taxe avec dividende à l'échelle d'un pays (ou de l'Union Européenne). Or, sans redistribution internationale pour contrer les inégalités, l'uniformité des taxes carbone entre pays n'est plus justifiée. Au contraire, il est alors juste que les pays à bas revenus aient une taxe plus faible que la moyenne (et vice versa), d'une part car une taxe uniforme serait en parité pouvoir d'achat plus élevée dans ces pays et les conduirait ainsi à des réductions d'émissions en proportion plus importantes que les autres, d'autre part car en les acculant à revoir leur consommation de certains produits de base, une même contraction des émissions affecterait plus durement les pays à bas revenus (Stern & Stiglitz, 2017). Dès lors que la taxe carbone varie selon les pays, il convient pour tout pays ayant une taxe élevée d'instaurer des tarifs douaniers dits « d'ajustement aux frontières », en taxant les émissions incorporées dans les importations au taux national diminué du taux du pays exportateur (Mehling et al., 2019). Cet ajustement permet d'éviter une fuite des émissions de gaz à effet de serre vers les pays avec de faibles niveaux de taxe [17]. Par ailleurs, pour s'assurer que la compétitivité d'un pays reste intacte lorsqu'il instaure une taxe élevée, l'ajustement à l'importation ne suffit pas, il faut aussi que le pays exempte (ou rembourse) ses exportations de la taxe carbone. Mais dans ce cas, pour une question de justice autant que d'acceptabilité internationale lors de négociations commerciales, les pays riches adoptant ces mécanismes devraient reverser les recettes de l'ajustement aux frontières dans un fonds contribuant à la lutte contre le

16. J'utilise désormais abusivement cette expression courante à la place de « prix sur les émissions ».

17. Il est à noter que, tandis qu'une simple taxe est facile à administrer car elle ne concerne qu'un petit nombre de producteurs à la source des émissions (compagnies pétrolières, cimenteries...), l'évaluation précise des émissions incorporées dans un produit (i.e. de son « empreinte carbone ») n'est possible qu'avec des données détaillées sur la chaîne d'approvisionnement de chaque entreprise : il serait utile à cette fin de répertorier toutes les commandes des entreprises dans un registre mondial.

changement climatique, comblant ainsi le manque de moyens dévolus à cette cause dans les autres pays. D'importants transferts supplémentaires seraient par ailleurs requis au titre des responsabilités nationales différenciées dans les émissions historiques de gaz à effet de serre (Höhne & Blok, 2005; Matthews et al., 2014).

Introduire une panoplie de mesures complémentaires

Une telle taxe carbone avec dividende et assortie d'un ajustement aux frontières est soutenue par des acteurs de tout bord dans de nombreux pays. Des variantes d'une telle mesure ont notamment été défendues par la plupart des économistes américains les plus célèbres (Baker et al., 2017) ainsi que par l'association européenne des économistes de l'environnement. En France, les acteurs semblent au diapason : tous recommandent une taxe carbone avec un dividende qui décroît avec le revenu, pour renforcer le caractère progressif de la mesure (ADEME, 2019; Conseil d'Analyse Économique, 2019; Conseil des Prélèvements Obligatoires, 2019; Haut conseil pour le climat, 2019; Iddri, 2019; Réseau Action Climat, 2019; Terra Nova I4CE, 2019). Pour autant, même si cette mesure présente des effets distributifs verticaux désirables (redistribuant en moyenne des riches aux pauvres), elle implique des effets distributifs horizontaux conséquents : pour un même niveau de revenu, certaines personnes gagneraient du pouvoir d'achat suite à la mesure tandis que d'autres en perdraient (West & Williams, 2004; Bureau, 2011). Si la taxe (aujourd'hui autour de 50 €/tCO_2) est portée à 500 €/tCO_2 en 2040 (suivant la trajectoire de la valeur de l'action pour le climat préconisée dans le rapport Quinet), des personnes au revenu médian gagneront 100 €/mois et d'autres en perdront autant, voire davantage (Douenne, 2020). Or, s'il tient compte de la psychologie humaine, un planificateur impartial doit reconnaître que les gains des uns ne compensent pas les pertes des autres, car les individus sont bien plus sensibles à une perte de niveau de vie qu'à une amélioration (Kahneman & Tversky, 1979). Par ailleurs, il est difficile de compenser ces effets distributifs horizontaux par des transferts monétaires sans mettre en péril l'effet incitatif de la taxe et donc les abattements qu'il engendre. En outre, même si ces disparités d'effets sur le pouvoir d'achat ne font que traduire le principe pollueur–payeur pour des personnes ayant des empreintes carbone différentes, beaucoup les trouvent injustes dans la mesure où des individus sont pénalisés à cause de choix dont ils sont peu responsables, notamment des investissements décidés à une époque où les émissions de gaz à effet de serre n'entraient pas dans les critères de décision (chaudière thermique, habitat pavillonnaire, automobile...). Certes, d'ici 2040 les gens ont le temps de changer leurs modes de vie : de déménager dans un logement plus petit et plus près de leur lieu de travail, de faire des travaux d'isolation ou d'installer une pompe à chaleur. Le temps nécessaire à ces adaptations est d'ailleurs un argument pour retarder l'entrée en vigueur de la taxe, celle-ci produisant déjà des effets (par anticipation) dès lors que sa trajectoire de prix sur le long terme est définie et crédible. Mais bien souvent, des ménages se retrouvent dans une situation de dépendance vis-à-vis des énergies fossiles car les alternatives sont inexistantes ou inabordables. Les locataires n'ont pas la maîtrise sur l'isolation ou la chaudière de leur logement tandis que les banques sont frileuses pour apporter des solutions de financement aux propriétaires qui souhaiteraient payer les travaux grâce aux économies d'énergie ; les transports publics sont trop peu fréquents ou leur desserte insuffisante pour se substituer à la voiture individuelle en zones rurales et péri-urbaines ; les routes n'offrent généralement pas de piste cyclable ; etc.

Aussi comme la puissance publique a la compétence de l'aménagement du territoire et qu'elle peut financer des projets de long-terme à haut rendement social même s'ils sont peu profitables et risqués à court-terme, il est souhaitable qu'elle finance des équipements à faible émissions : transports publics, rénovations thermiques, énergies renouvelables, etc. Dans la mesure où ces investissements sont financés par une mise à contribution des plus riches et bénéficient de façon disproportionnée aux plus modestes (c'est souvent le cas pour les transports publics), leur effet distributif est préférable à celui d'une taxe carbone. De tels investissements, comme toute politique d'abattement alternative, permettent de baisser le niveau de la taxe carbone requis pour obtenir une réduction d'émissions donnée. Or, leurs effets distributifs justifient souvent d'alléger ainsi la taxe carbone, car même si cela dévie de la solution minimisant les coûts, ces derniers sont répartis plus équitablement (Stiglitz, 2019). Cette même logique s'applique d'ailleurs à la surtaxation de produits disproportionnément employés par les plus riches, tels que le kérosène ou les voitures de sport. En outre, les investissements « verts » peuvent être avantageusement financés par l'endettement public (ou la monétisation), surtout dans un contexte comme le nôtre où beaucoup de gens cherchent un emploi [18]. En effet, dans un contexte où la production n'est pas à son plein potentiel, le multiplicateur budgétaire est supérieur à 1 : il a été estimé autour de 1,5 lors de la Grande Récession (Blanchard & Leigh, 2013). Cela signifie que le déficit public engendre davantage d'activité qu'il n'en commande, assurant la soutenabilité de l'endettement public. De plus, dans un contexte d'inflation faible et de taux d'intérêt durablement proche de 0, il n'y pas lieu de s'inquiéter des conséquences d'une hausse de l'inflation ou de l'endettement public (tant que celui-ci reste soutenable) (Blanchard, 2019). Enfin, même si le multiplicateur budgétaire était inférieur 1 en général, il serait possiblement supérieur à 1 dans le cas d'investissements verts, car certains travaux montrent que ceux-ci stimulent l'emploi, du fait qu'ils concernent des secteurs ayant une plus grande proportion de bas salaires que la moyenne, une part des salaires dans la valeur ajoutée plus élevée et (mais cela joue moins) une balance commerciale plus favorable (Bovenberg & van der Ploeg, 1994; Perrier & Quirion, 2018). En France, 630 000 emplois seraient ainsi créés d'ici 2030 dans un scénario de décarbonation complète (Quirion, 2013), et des résultats comparables sont attendus dans la plupart des pays (Bovenberg & Van der Ploeg, 1998; Ortega et al., 2015; Jacobson et al., 2017). Cette perspective d'une relance de la demande par la transition écologique est d'ailleurs ce qui sous-tend les propositions de « Green Deal » ou de « Green New Deal » de part et d'autre de l'Atlantique (Elliott et al., 2008; UNEP, 2009; DiEM25, 2017; Pacte Finance-Climat, 2018; Ocasio-Cortez, 2019; European Commission, 2019).

Diverses autres déviations par rapport au « modèle standard » justifient d'autres politiques climatiques que la seule taxe carbone. L'instauration de normes voire d'interdictions est justifiée sur les produits ayant plusieurs versions équivalentes sur le plan fonctionnel, lorsque (contre toute logique économique) les consommateurs n'achètent pas la version la plus économe en énergie : c'est le cas des ampoules par exemple (Stiglitz, 2019). Aussi, comme les innovations concernant les technologies « vertes » bénéficient à tous et passeulement à leur inventeur (après quelques années, même leurs concurrents peuvent se les approprier), le secteur privé investit moins dans la recherche et développement que ce qui serait optimal pour la société (Acemoglu et al., 2012). La collectivité peut alors compenser ce sous-investissement en subventionnant l'innovation « verte » ou en imposant des normes qui contraignent le secteur privé à innover, comme pour les normes d'émission sur les véhicules (EPA, 2010; Reynaert, 2014; Klier & Linn, 2016). Enfin, des normes d'émission sur les véhicules peuvent aussi être justifiées d'une autre façon : dans la mesure où un certain statut est

18. Au quatrième trimestre 2019, il y avait en France 2,4 millions de chômeurs au sens du BIT et 1,7 millions de personnes dans le halo autour du chômage (en recherche d'emploi mais inactives au sens du BIT), cf. insee.fr/fr/statistiques/4309346.

conféré à un automobiliste par des caractéristiques de son véhicule (comme le poids) directement liées à son facteur d'émission (Johansson-Stenman & Martinsson, 2006; Carlsson et al., 2007), il convient de taxer les véhicules polluants au-delà du taux normal (Howarth, 1996) ou, de façon équivalente, d'imposer des pénalités pour tout facteur d'émission en excès par rapport à une norme. Plus précisément, cette justification est valable si la mesure en question n'a pas d'effet distributif défavorable et si elle permet de réduire la surconsommation de véhicules polluants induite par leur positionalité (i.e. leur effet de statut) ou de la déporter vers d'autres biens positionnels moins polluants (tels que les voitures électriques, les œuvres d'art, ou la philanthropie).

Reconnaître les obstacles à une société décarbonée

Un programme idéal de décarbonation contiendrait donc différentes mesures ciblant autant de problèmes spécifiques, structurées autour d'une taxe carbone avec dividende afin d'aligner les choix de toute la société sur l'objectif climatique. Mais demeure une question essentielle : les gens sont-ils prêts à bousculer leur mode de vie (à prendre peu l'avion, à manger peu de viande, etc.) ? Cela n'a rien d'évident qu'une majorité accepte ces mesures, même si elles ont été conçues pour compenser financièrement le plus grand nombre. Pour cela, il faut que la plupart des électeurs comprenne les enjeux climatiques, soutienne les objectifs de réductions d'émissions, souscrive aux justifications des mesures proposées, et accorde confiance au gouvernement pour leur mise en œuvre. La réunion de ces conditions n'a rien d'évident, d'autant plus que les effets des différentes mesures sont incertains pour chacun : par exemple, qui peut prévoir comment la valeur de sa maison va être affectée par la décarbonation et le nouvel aménagement du territoire qu'elle implique ? Or, l'aversion à la perte favorise l'inaction du *statu quo* en de telles situations d'incertitude (Stiglitz, 2019).

Outre cet obstacle d'acceptabilité politique de la décarbonation, une potentielle limite physique a attiré mon attention lorsque j'ai réfléchi à ces questions. Un système énergétique reposant uniquement sur les énergies renouvelables serait-il viable et efficace ? Certes, des plans de transformation du système énergétique vers le tout renouvelable ont été proposés, mais ils négligent le coût énergétique de la construction du système énergétique lui-même. Ou plutôt, ils considèrent qu'une éolienne ou un panneau solaire requerra autant d'énergie pour être fabriqué dans un monde décarboné qu'aujourd'hui. Or, il apparaît que la fabrication d'éoliennes ou de panneaux solaires requiert plus d'énergie que celle de centrales thermiques (Weißbach et al., 2013). Donc, si les éoliennes et les panneaux solaires sont fabriqués en utilisant de l'électricité d'origine renouvelable plutôt que fossile, l'énergie nécessaire (tout au long de la chaîne d'approvisionnement) pour leur fabrication augmente. Il est donc crucial de savoir si cet effet compromet ou non l'efficacité des énergies renouvelables à fournir de l'énergie.

Enfin, un autre obstacle à une civilisation décarbonée est qu'elle repose malgré tout sur des ressources finies : les métaux. En effet, aucune industrie ne serait possible sans métaux, et c'est particulièrement vrai pour la production d'énergie renouvelable, très intensive en métaux (Hertwich et al., 2015). Or, quand on considère l'énergie phénoménale qui serait requise pour récupérer l'intégralité du métal qui composait nos produits en fin de vie (dont une partie est dissipée dans l'environnement et une autre diluée dans des alliages), il est plausible que cette énergie dépasse celle que nous pouvons délivrer en construisant des centrales électriques à partir de ce métal. Cela signifie qu'un métabolisme industriel strictement circulaire est impossible, et que le recyclage sera nécessairement partiel. Certes, en pratique, la recyclabilité et les ressources minières sont peut-être suffisamment élevées pour assurer à l'humanité de ne pas manquer de métal pendant des millions d'années, mais rien ne le garantit. Au contraire, certains spécialistes prévoient un pic de l'extraction de cuivre d'ici le milieu du XXI^{e} siècle et prévoient un épuisement de la ressource d'ici deux siècles (Gordon et al., 2006; Henckens et al., 2014; Kerr, 2014; Sverdrup et al., 2014). Certes, ces prévisions alarmistes emploient une définition abusivement étroite de ce qui constitue une ressource en cuivre, mais même les estimations plus optimistes suggèrent un épuisement d'ici quelques milliers d'années (Kesler & Wilkinson, 2008). Il est donc légitime de faire l'hypothèse d'une recyclabilité partielle et de ressources finies, et d'étudier le calendrier optimal d'extraction nécessaire à la production d'énergie, sachant qu'on dispose de métal et d'hydrocarbures fossiles. [19]

Mon travail de thèse a consisté à analyser ces trois obstacles à l'apparition d'une société décarbonée durable.

19. Si on considère que l'humanité va vivre indéfiniment, alors le problème est insoluble d'un point de vue éthique (car il est impossible de partager une ressource finie en une infinité de parts). Mais dans la mesure où il y a une probabilité positive d'extinction à chaque période, il est justifié que les premières générations exploitent la ressource (de façon raisonnée).

Résumé

Tant les effets désastreux d'un changement climatique non atténué que l'épuisement des combustibles fossiles exigent une transition vers un système énergétique décarboné. Dans cette thèse, je me demande si et comment une civilisation industrielle décarbonée et durable peut être réalisée, en étudiant certains aspects de sa faisabilité physique et de son acceptabilité politique. Chaque chapitre s'inscrit dans la littérature économique et emprunte des méthodes à l'économie (maximisation du bien-être intertemporel, méthode des variables instrumentales, enquêtes représentatives, analyse entrées-sorties...), tout en étant lié à une autre discipline (écologie industrielle, mathématiques, sciences comportementales ou sciences politiques). Malgré une motivation commune pour comprendre les conditions de la transition énergétique, chaque chapitre est autonome par rapport aux autres.

Alors que les combustibles fossiles devraient être remplacés par les métaux comme principaux intrants de la collecte d'énergie, je montre au Chapitre I qu'il n'a jamais été établi qu'une telle transition énergétique serait physiquement soutenable, dans le sens où un secteur électrique décarboné fournirait un surplus d'énergie à la société. En effet, la capacité à fournir un surplus d'énergie n'est pas une propriété intrinsèque d'une technologie, car elle dépend de l'ensemble de la chaîne de production. Ainsi, on ne peut pas déduire les surplus énergétiques dans un scénario décarboné à partir de la seule mesure des surplus énergétiques *actuels*. Mon chapitre répond à cette problématique et prédit que l'efficacité globale du secteur de l'électricité à fournir de l'énergie serait réduite de moitié dans un scénario 100% renouvelable. Je conclus l'analyse en étudiant le lien entre le prix de l'énergie et son efficacité (mesurée par le taux de retour énergétique).

Comme les énergies provenant de sources fossiles et renouvelables coexisteront pendant la transition, et dans la mesure où les ressources en métaux (nécessaires pour collecter l'énergie renouvelable) sont finies, il est intéressant de connaître la trajectoire optimale d'extraction des fossiles par rapport aux métaux. Dans le Chapitre II, qui est un travail conjoint avec Mouez Fodha et avec Francesco Ricci, nous répondons à cette question et soulignons l'importance de la recyclabilité des métaux. Nous constatons que plus la recyclabilité est élevée, plus la transition vers les énergies renouvelables devrait se faire rapidement, même sans aucune pollution par les fossiles.

La démonstration rigoureuse de l'optimalité de la solution à notre problème d'optimisation convexe est apparue fastidieuse, car nous ne pouvions pas appliquer le théorème de Karush-Kuhn-Tucker à notre programme à horizon infini. J'ai été surpris de constater que ce théorème, largement utilisé par les économistes, n'avait pas d'extension à un nombre dénombrable (infini) de variables, et ai donc entamé une collaboration avec les mathématiciens Mohammed Bachir et Sebastián Tapia García. Dans l'Annexe D au Chapitre II, nous dérivons les conditions d'optimalité et de Gateaux-différentiabilité des fonctions convexes dans certains espaces de dimension infinie (les espaces de Banach admettant une base de Schauder). Le théorème de Karush-Kuhn-Tucker s'étend

naturellement au cas d'une fonction convexe avec un nombre dénombrable de variables (telles qu'une série) et un nombre fini de contraintes. Ainsi, sous des hypothèses minimales, une solution aux conditions de premier ordre d'un lagrangien à horizon infini est nécessairement un optimum.

Après une première partie de la thèse ayant permis de dissiper des doutes quant à la faisabilité physique d'une transition vers les énergies renouvelables et de comprendre les enjeux liant énergie, métaux, et recyclabilité, l'irruption du mouvement des Gilets jaunes fut un signe que le facteur limitant de la décarbonation est son acceptation politique. J'étudie donc dans la deuxième partie de la thèse les contraintes politiques qui pèsent sur la décarbonation, c'est-à-dire les croyances et les préférences qui permettent ou empêchent l'atténuation du changement climatique. Une note en français de 7 pages synthétise cette partie : Douenne & Fabre (2019).

Dans un travail commun avec Thomas Douenne, nous avons analysé les politiques climatiques soutenues par les Français en réalisant une enquête en ligne sur un échantillon représentatif de trois mille personnes. Dans le Chapitre III, nous démêlons les préférences des croyances relatives à une taxe carbone avec dividende, mesure progressive fiscalement et préconisée par de nombreux économistes pour lutter contre le changement climatique et réaliser la transition énergétique à moindre coût. Nous constatons que si 70 % rejettent la taxe carbone, c'est en raison de perceptions pessimistes quant à ses propriétés : en contradiction avec nos micro-simulations, la plupart pensent que leur ménage perdrait en pouvoir d'achat avec la réforme, la perçoivent comme régressive et inefficace pour réduire la pollution et lutter contre le changement climatique. Le pessimisme dans les croyances ne peut être facilement corrigé en fournissant de nouvelles informations aux personnes interrogées, car seule une minorité d'entre elles révise correctement leurs réponses. Toutefois, cette minorité de personnes convaincues nous permet d'identifier robustement des effets causaux, quand la littérature antérieure n'établissait que des corrélations : le taux d'acceptation de la réforme augmente d'environ 50 points de pourcentage lorsqu'une personne ne pense pas perdre suite à la réforme, ou lorsqu'elle croit en l'efficacité environnementale de celle-ci ; et l'approbation est de 90% pour les personnes qui croient en plus que la réforme est progressive. Si le rejet de la taxe carbone résulte de croyances pessimistes quant à ses propriétés qu'on peut lier à une méfiance envers l'État, nous contribuons aussi à la littérature sur la formation des croyances politiques en montrant que celles-ci pourraient provenir de *raisonnements motivés* par un rejet primitif de la mesure, que nous qualifions d'*aversion à la taxation*, et qui peut être rationalisé par la psychologie sociale.

Dans un article compagnon, qui constitue le Chapitre IV, nous étudions le rapport des Français au changement climatique et aux politiques climatiques en général. Nous analysons les connaissances, les perceptions et les valeurs liées au changement climatique, nous examinons les opinions relatives à la taxation du carbone et nous évaluons le soutien à d'autres politiques climatiques. Parmi les nombreux résultats obtenus, nous constatons que les connaissances sur le changement climatique sont limitées bien que celui-ci suscite une grande inquiétude, et nous documentons un soutien majoritaire à des régulations plus strictes et à des investissements verts. Nous constatons que l'inquiétude vis-à-vis du changement climatique augmente avec les connaissances à son sujet, ce qui suggère qu'un meilleur accès à la science pourrait augmenter le soutien aux politiques climatiques. Enfin, la position par rapport aux Gilets jaunes apparaît comme le meilleur prédicteur des préférences environnementales, rendant moins pertinent le spectre traditionnel gauche–droite.

Preamble

Understanding climate change

The rapid growth in population and consumption underway since the industrial revolution has been sustained by the combustion of fossil hydrocarbons (coal, oil, gas), which provide 85% of the world's primary energy use (BP, 2019). The main product of this combustion is carbon dioxide (CO_2) : its concentration in the atmosphere has increased from 280 particles per million (ppm) before the industrial revolution to 415 ppm in 2020 (Meinshausen et al., 2017). CO_2 is a greenhouse gas : it absorbs the Earth's infrared radiation and converts its electromagnetic energy into thermal energy, trapping this energy in the atmosphere in the form of heat. While about half of CO_2 emissions are absorbed within a century by the biosphere (through plant growth by photosynthesis) or by the hydrosphere (through the dissolution of CO_2 in the ocean until thermodynamic equilibrium), 10 to 20% of them remain in the atmosphere for thousands of years, permanently altering the climate (Archer et al., 2009; Jones et al., 2013; Millar et al., 2017). Remarkably, the temperature anomaly with respect to the pre-industrial period is well approximated by the cumulative amount of anthropogenic greenhouse gas emissions (Allen et al., 2009; Matthews et al., 2009). Thus, only carbon neutrality (i.e., stopping these emissions or offsetting them by removing CO_2 from the atmosphere) would halt the climate change induced by the alteration of atmospheric composition, while a return to a concentration of 350 ppm by net removal of CO_2 would be required for the climate to stabilize around current climate conditions (Hansen et al., 2013).

If, on the contrary, greenhouse gas emissions continue to increase along the past trend until 2100 and then decrease linearly to 0 in 2300, then the CO_2 concentration would reach 1000 ppm in 2100, 2000 ppm in 2300, and the temperature anomaly would be +4°C in 2100, and up to +7-8°C between 2300 and 5000 (Montenegro et al., 2007). The Earth would then reach temperatures unmatched in 20 million years (Zachos et al., 2008). In a similar emissions scenario (IPCC's RCP 8.5 scenario[20]), melting of the Western Antarctic ice sheet could raise sea level by 15 meters by 2500 (DeConto & Pollard, 2016) and submerge coastal areas currently home to 950 million people by 2300 (Kopp et al., 2017). In a more extreme scenario, where even more fossil hydrocarbons would be burned, the temperature anomaly could reach +16°C, making most of the land uninhabitable for mammals (such temperatures causing lethal hyperthermia) (Hansen et al., 2013). Even in the RCP 8.5 scenario, large areas of China, South Asia and the Middle East would be rendered uninhabitable in the 22nd century due to wet-bulb temperatures regularly exceeding the lethal value of 35°C (which does not occur anywhere in the current climate) (Pal & Eltahir, 2016; Im

20. More specifically, the International Panel on Climate Change (IPCC) has defined four reference trajectories for greenhouse gas concentrations, the Representative Concentration Pathways (RCPs), designated by their radiative forcing in the year 2100 (8.5 W/m^2 for RCP 8.5, IPCC, 2013).

et al., 2017; Kang & Eltahir, 2018). In a less extreme emissions scenario (the RCP 4.5 scenario), with a temperature of +2°C in 2100 and +2.5°C in 2300, the temperature would correspond to that of the last interglacial period (125,000 years ago) (Snyder, 2016) where sea level was 6 to 9 meters higher than today, mainly due to the melting of the poles (Turney et al., 2020). In this scenario, a similar sea level rise can be expected in the future, as sea level is mainly due to temperature. But even if this new equilibrium would not be reached for several hundred years, by 2100 sea level would (in the absence of dykes) submerge areas where 250 million people currently live (Kulp & Strauss, 2019), and where strong population growth is expected (Neumann et al., 2015). Rising water levels will mean that entire cities will have to be relocated when dyke protection proves impossible or too expensive to build (Hinkel et al., 2014; Diaz & Moore, 2017). In general, our infrastructure (and land uses) are adapted to the current climate and climate change will make many of them obsolete, if not simply destroyed (CCR, 2018). As a result of climate change, freshwater availability (through precipitation and rivers) is expected to increase in some regions (Europe, South-East Asia, East Coast of the United States) but decrease in others, including the most populated (China, South Asia), leading to more droughts and increased water scarcity (Elliott et al., 2014). Also, Schlenker & Lobell (2010) estimate that, in the absence of adaptation measures, climate change will lead to a drop in agricultural yields of about 20% by the middle of the century for the main crops in sub-Saharan Africa. A warming of 2 or 3°C, on the other hand, would lead to decreases in agricultural yields against which even adaptation measures would be ineffective (Moore et al., 2017). Besides, as of 2000, 166,000 deaths per year were attributable to climate change, mainly because of its consequences in terms of malnutrition, diarrhea and malaria in Africa and South Asia (Patz et al., 2005). And that does not include the 6 million annual deaths due to air pollution caused by fossil fuels (Gakidou et. al, 2017). Moreover, high temperatures are associated with lower productivity, against which adaptation seems impossible (Burke & Tanutama, 2019), especially for outdoor activities (Behrer et al., 2019). In summary, continued greenhouse gas emissions would jeopardize multiple segments of society (Dell et al., 2012; Carleton & Hsiang, 2016), increasing the likelihood of violent conflict (Burke et al., 2009) and leading to significant population displacement (Cattaneo et al., 2019).

Going beyond the age of fossil hydrocarbons

If we continue greenhouse gas-emitting activities such as fossil fuel combustion over the long term, the only way to contain the rise in atmospheric CO_2 concentration is to remove it from the atmosphere.[21] Reforestation and better land use are the preferred solutions to achieve this removal, but their potential is limited and will quickly be saturated, even in the most voluntarist scenarios (Griscom et al., 2017).[22] Sequestration is generally based on the preservation of newly

21. The average rise of temperature could certainly be avoided despite a rise in CO_2 concentration, thanks to climate engineering techniques such as the injection of sulfate aerosols into the stratosphere (these gases are known to dim and therefore cool the planet). However, all specialists agree that such an approach should not substitute decarbonization, as it presents serious problems : collapse of precipitation, acidification of the oceans, exacerbated global warming if the injection is interrupted, etc. (Robock et al., 2009).

22. In the case of reforestation, the capture of CO_2 is obtained naturally through photosynthesis, which is the source of plant growth, and it was once envisaged to fertilize the oceans by injecting iron or other nutrients (phosphorus, nitrogen), as these are the limiting factors for phytoplankton growth (Coale et al., 1996). Indeed, during a biochemical process called the "biological pump", part of the CO_2 absorbed by phytoplankton during photosynthesis is deposited on the ocean floor in the form of calcium carbonate, where it is then sequestered in the sediments for millions of years. However, the effects of ocean fertilization are uncertain and potentially harmful or counterproductive, as it can induce by eutrophication dead zones that release methane and other greenhouse gases more potent

created biomass, although greater use of timber would also provide carbon storage. It has also been proposed to cut and bury timber (Scholz & Hasse, 2008), but this would require the conversion of much of the world's forests to this use (Köhl & Frühwald, 2009). Another removal option is to use biomass as a fuel in thermal power plants producing heat and electricity, where the CO_2 from the stacks can then be captured and sequestered artificially. The value of this solution varies from project to project : some projects use agricultural waste and are efficient, but others encroach on agricultural land or have a carbon footprint that is too high relative to the CO_2 extracted (and sometimes even higher European Academies Science Advisory Council, 2019). In addition to biomass power plants, capture can be done in the stacks of any plant that burns fuel, which can significantly reduce emissions from a thermal power plant for example (IEA, 2016). Artificial sequestration is currently carried out in sealed geological cavities, including former oil wells (IPCC, 2005). Stack capture and sequestration are already deployed on an industrial scale as they are used for enhanced oil recovery : CO_2 injections restore sufficient pressure to pump the remaining oil from wells close to exhaustion (oil that, when burned, emits the equivalent of at least half of the CO_2 injected to extract it, Mac Dowell et al., 2017). The direct capture of CO_2 from the air is also possible, but exists for the moment only at the prototype scale through a dozen experimental projects (Ishimoto et al., 2017) and requires as much energy as it was delivered by the combustion of the hydrocarbons that were the source of the captured CO_2 (Ranjan & Herzog, 2011).

These solutions are costly, have not all reached the stage of industrial maturity, and are based *a priori* on the geological storage capacities. Estimates of these capacities are unreliable, but they correspond to between 50 and 400 years of current emissions (IPCC, 2005). It is therefore unlikely that there is sufficient capacity to store the CO_2 that would be emitted if all fossil hydrocarbon resources were burned, which corresponds to at least 1000 years of current emissions (mainly in the form of coal) (Johansson et al., 2012). Moreover, as important as fossil resources are, they are finite and will be depleted within a few thousand years if their consumption continues at the current rate. It is likely that humans will still live for tens of thousands of years, if not millions of years. In this case, this means that our descendants will one day experience an energy system that is not based on fossil hydrocarbons. Whether fossil hydrocarbons are in short supply or whether their use poses more problems than it solves, the prospect of a decarbonized industrial civilisation is opened up. Thus, it is legitimate to question the possibility of a sustainable energy system based solely on mastered renewable energy sources, given the finite nature of uranium and plutonium resources (which are of the same order of magnitude as fossils if breeding is employed, Johansson et al. 2012) and the fact that the industrial deployment of other nuclear technologies (thorium, fusion) is far from certain.

Choosing the level of climate ambition

In order to decide to decarbonize the industrial metabolism, we need to know what value we attribute to a carbonized energy system and a stabilized climate on the one hand, and compare it to the value of comfort provided by fossil fuels on the other. Then, to the extent that we decide to decarbonize the energy system, it is necessary to set the speed and extent with which we do

than the sequestered CO_2 (Chisholm et al., 2001; Lampitt et al., 2008). As a result, several scientists have called for the idea to be abandoned, since for an experiment to properly measure both the potential for sequestering CO_2 and the side effects of fertilization, it would have to be conducted on a large scale over a 100-year period, at which time marine ecosystems would be at risk (Strong et al., 2009).

so, assigning a value to the possible climates in each emissions scenario, and comparing it to the efforts involved in the more or less rapid and profound transformation of our lifestyles required by each scenario. This trade-off is complicated by the fact that it involves comparing uncertain situations and at different times, but above all comparing one's well-being with the well-being of others. From the point of view of an impartial planner, this trade-off is necessarily based on ethical rules that make it possible to compare the well-being of different generations as well as populations that differ in terms of income, dependence on fossil fuels and vulnerability to climate change (itself a combination of exposure to its impacts and adaptive capacity, which is closely linked to wealth). The method favored by economists to assemble all these considerations and calculate the optimal decision is the integrated modeling of the economy and the climate. Numerous models have been proposed, which differ in their modeling choices but are all made up of four basic elements.

First, the social welfare function describes the objective to be optimized and incorporates both ethical and pragmatic considerations. Although it is recognized that ethically, no one population should be favored over another (Ramsey, 1928; Gollier, 2017) ; in practice, decision makers often favor their compatriots over foreigners and their generation over the next ones. Nevertheless, some authors adopt an ethical approach : they give equal weight to each human of a generation, and only depreciate the value of a generation to the extent that its existence is made uncertain for exogenous reasons (e.g., due to meteorite extinction) (Chichilnisky, 1996; Stern et al., 2007). On the other hand, other authors prefer to formulate recommendations in line with the assumed limited level of altruism of policymakers (Nordhaus & Sztorc, 2013; Rezai & Van der Ploeg, 2016; Dietz & Venmans, 2019) : they give less weight to the welfare of the least influential populations, substantially depreciating each generation relative to the previous one, and freezing income differences between countries (Stanton, 2011) [23] (which contradicts the ethical implication of redistribution arising from the usual assumption that individual well-being depends solely on income). Besides, the social welfare function incorporates other difficult ethical choices, such as inequality aversion (Fleurbaey & Zuber, 2012; Anthoff & Emmerling, 2019), risk aversion (Weitzman, 2009; Heal & Millner, 2013; Jensen & Traeger, 2014), or the relative preference between the population size its welfare level (Scovronick et al., 2017). Second, assumptions on climate and economic dynamics make it possible to estimate future climate based on the trajectory of greenhouse gas emissions and other human activities affecting the climate, and to establish a credible scenario for the evolution of organizational and technical progress as well as social behavior (in terms of savings, fertility, etc.). Models are sometimes stochastic in nature to account for the limited knowledge on these dynamics. Thirdly, the models include a damage function, which evaluates damages related to climate change for each possible climate, the latter being often summarized by the global temperature anomaly and sometimes also by the sea level. This damage function generally aggregates damage to capital, production, health, and biodiversity, and converts it into income loss (Moore & Diaz, 2015; Howard & Sterner, 2017). Fourth, the models include a marginal abatement cost curve, which links each additional reduction in greenhouse gas emissions to its cost. Thus, such models are agnostic on the emission reduction technologies to be implemented, as they assume that the choice of these technologies depends only on their cost, or at least that the only relevant

23. As (Stanton, 2011) writes : "Modelers have viewed the tendency toward equalization of incomes across regions as a problem, where the solution is to constrain the model to view the marginal utility of income as being the same in every region (in any given time period). A set of 'Negishi weights' is included in the regional utility functions such that the weighted contribution to social welfare of one dollar of additional consumption is the same in all regions. Higher weights are assigned to welfare in richer countries, while welfare in poorer countries receives lower weights. This procedure obviates the IAMs' [integrated assessment models] equalization of income."

parameters for the decision are the emission reduction and its cost (which impacts consumption and thus welfare) (Enkvist et al., 2007; Kesicki, 2011). This convertibility between the different types of damage and the different forms of emission reductions into a single cost concept makes it possible to arbitrate between the extent of damage and the effort to reduce emissions. Indeed, the optimal level of effort is defined as the one for which the planner is indifferent between providing or not providing an additional effort to reduce emissions, the cost in terms of damage thus avoided being then equal to the corresponding additional abatement cost. This cost generally increases over time and is referred to as the "social cost of carbon", as it corresponds to a cost (in terms of damage or abatement) that is not borne specifically by the emitter of emissions (unlike the cost of fuel), but is spread over society as a whole. Some simple models provide an analytical expression for the optimal trajectory of the social cost of carbon (Golosov et al., 2014; Traeger, 2015; Rezai & Van der Ploeg, 2016; van den Bijgaart et al., 2016; Dietz & Venmans, 2019), while more sophisticated models calculate numerically the trajectory that maximizes the social welfare function (Bosetti et al., 2006; Hourcade et al., 2010; Hope, 2011; Stehfest, Elke et al., 2014; Anthoff & Tol, 2014; Nikas et al., 2019).

Envisioning the transformation of the productive system

An alternative approach, which stems from the functioning of climate negotiations and international treaties (Kyoto, Paris), consists of a two-step approach. In the first stage, a climate target is decided, often expressed in terms of temperature anomaly, and its value is guided both by integrated modeling results and by more basic considerations of what constitutes the limit of acceptable climate change. In a second step, this objective is incorporated as a constraint in the integrated models, thus rendering the damage function obsolete. Each model then gives a trajectory for the cost of greenhouse gas emissions that makes it possible to meet the climate objective while ensuring an optimal distribution of abatement efforts over time. The cost of emissions is in this case called the "value of climate action" (Quinet, 2019) because it represents the value we place on the future and on others through the transformation of our lifestyles that allows us to achieve our climate objective. This value of climate action is also called the "shadow price" of emissions, because, in a market without any failure and in line with the "polluter pays" principle, it represents the price on emissions that enables the emissions trajectory indicated by the model to be achieved. Indeed, to the extent that greenhouse gas emissions become priced, economic agents will reduce their emissions, either by simple budgetary constraints or by substituting their polluting activities with other activities that are made comparatively cheaper. The marginal abatement cost curve is then the key element in determining the value of climate action, as it gives the emission price required to achieve each degree of abatement. The observation of this curve shows us that among the cheapest abatements is the decarbonization of the electricity mix. Indeed, forcing coal-fired power plants to pay €30 for each ton of CO_2 they emit would be enough to make electricity from renewable sources competitive with that from old coal-fired plants,[24] which is often still the cheapest (Kesicki & Ekins, 2012). In some cases, depending on local specificities, coal-fired power plants could remain competitive despite a high emission price, by capturing and sequestering CO_2 from their stacks : this would only be the case when this capture and sequestration would cost less than the emissions avoided, and when the additional cost they would induce would remain below the addi-

24. This figure is a world average. In Europe, it is rather around 100 €/tCO_2 that electricity from renewable sources would be competitive with that from thermal power plants (RTE, 2016).

tional cost of electricity from renewable sources. However, in any case, a sufficiently high emission price would decarbonize the electricity mix. Similarly, with an even higher emission price, between 100 and 500 €/tCO_2, unsubsidized electric cars would become competitive with combustion cars, and building insulation would become truly profitable (Quinet, 2019). On the other hand, carbon neutrality seems very difficult for certain sectors whose emissions are not exclusively due to the use of fossil fuels : this is notably the case for agriculture, cement production and steel production. Offsetting emissions from these sectors will probably require the use of a “backstop technology” to capture and sequester atmospheric CO_2. The price of such a technology will then correspond to the long-term value of climate action, when we will offset each anthropogenic emission of greenhouse gases by a corresponding removal from the atmosphere. Indeed, if an agent has to pay to add CO_2 to the atmosphere, it makes sense that an agent that removes it in a sustainable way should be paid an equivalent amount. The technologies for direct air capture of CO_2 mentioned above are almost backstop technologies, and could become profitable starting at 200 €/tCO_2 or even 20 €/tCO_2 according to engineers in this emerging industry (Ishimoto et al., 2017; Keith et al., 2018; Breyer et al., 2019; Fasihi et al., 2019) but not below 1000 €/tCO_2 according to skeptical academics (Ranjan & Herzog, 2011; House et al., 2011). However, these technologies are not totally “backstop” because they rely on limited storage capacity and therefore only offer a solution for the next few centuries, but not for the very long term. Therefore, a truly backstop (but likely more expensive) technological solution would be to convert CO_2 into a chemically stable solid or liquid (not gaseous) form, such as calcium carbonate ($CaCO_3$) or hydrocarbons obtained by artificial photosynthesis. However, as research on such processes is still in its infancy, it is too early to estimate the cost of a truly backstop technology (Ma et al., 2009; Li et al., 2014).

Once emission and price trajectories are established, other models are used to detail the investments to be made in a specific sector. For example, a bottom-up engineering model can be used to optimize the power generation system on a continental scale such as Europe. The model takes into account existing power plants, their lifetime, the hourly production potential at each point on the continent, and determines the investments to be made to meet a demand scenario at the lowest cost, possibly under the constraint that certain technologies are set aside. Using such a model, the International Energy Agency has thus calculated the optimal evolution of energy systems in each region of the world by 2050, according to different emission scenarios (IEA, 2010). Similarly, in a report commissioned by Greenpeace (Teske et al., 2015), a team of researchers calculated the optimal energy system under the constraint that all the world’s energy should come from renewable sources by 2050. This report is not an isolated work : other works have shown how it is possible to decarbonize our economy completely and quickly (García-Olivares et al., 2012; Jacobson et al., 2017; Scholz et al., 2017). A common feature of all these prospective exercises is the diversity of technologies employed : there is no single miracle technology that would become hegemonic ; on the contrary, the optimal system consists of most of the known decarbonized technologies. This is due to the diversity of uses, the diversity of potentials according to regions, and the unit costs of a technology generally increasing when its share in the mix becomes large.

Pricing greenhouse gas emissions

Once the scale of emission reductions has been decided and the concrete implications in terms of transforming the production system have been assessed, it remains to determine the best public policy mix to achieve the transition. In a society with a fair distribution of wealth and a market with no other shortcoming than the absence of a price on greenhouse gas emissions, the optimal measure is to impose a single price on all greenhouse gas emissions, equal to the social cost of carbon (Pigou, 1920). Rather than favoring particular abatement methods, a uniform price on emissions ensures that the abatement is done at the lowest cost, because the abatements implemented are exactly those that cost less than the price of the emission avoided. It is the assumed rationality of the agents that ensures that no abatement costs will be squandered and that all cost-effective abatements will be undertaken. The emission price can be revised regularly as we refine our estimates of the parameters that allow us to calculate it (abatement costs, climate dynamics, climate change damage...) or because of a change in our preferences (altruism for future generations, risk aversion). This price can come from a tax, a market for emission permits auctioned by the authorities within the limit of a global allowance, or a combination of both (a permit market with a floor price and a ceiling price, for example), and it is the latter solution that is optimal (Weitzman, 1974; Pizer, 2002). However, if the amount of the tax or the overall emissions allowance is reviewed regularly, the differences between tax and permit market become blurred. The only parameter that remains decisive is the level of the price (or quota) : this could be determined by the median of votes in a world assembly to ensure the democratic principle of "one person : one vote" (Weitzman, 2017).

Far from this fictitious stylized economy, today's society requires the implementation of a range of measures to combat climate change. While a price on emissions provides a useful benchmark against which to evaluate other public policies (and in particular their abatement costs), relying on price alone cannot be the optimal solution for several reasons. The main reason is the wide disparities in income, wealth, and dependence on fossil fuels. Indeed, the carbon tax [25] leads to large distributional effects, which often aggravate inequalities. Since (on average) the share of income spent on fuel decreases with income, a carbon tax tends to increase inequalities in purchasing power (Williams et al., 2015). This distributional effect may also explain why decisions to increase fuel prices triggered the Yellow Vests movement in France and massive demonstrations in Ecuador and Iran. This regressive nature of the carbon tax can, however, be corrected if the revenues it generates are used in a redistributive manner (which was not the case in the three examples cited above).

Redistributing the revenues of a global carbon tax equally to each human on a monthly basis would be equivalent to allocating the same tradable emission permit to each human, which is quite elegant from a normative point of view. Thus, those responsible for more emissions than average would lose more purchasing power from price increases than they would gain from the redistributed revenues, and vice versa. Such redistribution would make this "carbon tax with dividend" progressive and would partially correct current income inequalities. That said, the division of the world into nations and the intergovernmental format of climate negotiations favor nationalist positions and thwart plans involving transfers of wealth between countries. As a result, many commentators are resigned to proposing the implementation of a tax with dividend at the level of a country (or of the European Union). However, without international redistribution to counter inequalities, the uniformity of carbon taxes between countries is no longer justified. On the contrary, it is then fair that low-income countries should have a lower than average tax (and vice versa), on the one hand because a uniform tax would have a higher purchasing power parity in these countries and would thus lead them to proportionally greater emissions reductions than others, and on the other hand because by forcing them to review their consumption of some basic commodities, the same contraction in emissions would affect low-income countries more severely (Stern & Stiglitz, 2017). Since

25. I henceforth abusively use this common expression instead of "price on emissions".

the carbon tax varies from one country to another, it is appropriate for any country with a high tax to introduce so-called "border adjustment" tariffs, by taxing emissions embodied in imports at the national rate minus the exporting country's rate (Mehling et al., 2019). This adjustment avoids a leakage of greenhouse gas emissions to countries with low tax levels.[26] Furthermore, to ensure that a country's competitiveness remains intact when it introduces a high tax, import adjustment is not enough, the country must also exempt (or refund) its exports from the carbon tax. But in this case, for reasons of justice as well as international acceptability at trade negotiations, rich countries adopting these mechanisms should transfer the revenues from border adjustment into a climate change fund, thus making up for the lack of resources devoted to this cause in other countries. Besides, substantial additional transfers would also be required as a result of differentiated national responsibilities for historical greenhouse gas emissions (Höhne & Blok, 2005; Matthews et al., 2014).

Introducing a range of complementary measures

Such a carbon tax with dividend and border adjustment is supported by agents from all sides in many countries. Variants of such a measure have notably been advocated by most prominent US economists (Baker et al., 2017) as well as the European Association of Environmental and Resource Economists. In France, the protagonists seem to be in tune : all recommend a carbon tax with a dividend that decreases with income, to reinforce the progressive nature of the measure (ADEME, 2019; Conseil d'Analyse Économique, 2019; Conseil des Prélèvements Obligatoires, 2019; Haut conseil pour le climat, 2019; Iddri, 2019; Réseau Action Climat, 2019; Terra Nova I4CE, 2019). However, even if this measure has desirable vertical distributional effects (redistributing on average from the rich to the poor), it implies significant horizontal distributional effects : for the same level of income, some people would gain purchasing power as a result of the measure while others would lose some (West & Williams, 2004; Bureau, 2011). If the tax (currently around 50 €/tCO_2) is increased to 500 €/tCO_2 in 2040 (following the value for climate action recommended in the Quinet report), some people with median income will gain 100 €/month while some others will lose as much, or even more (Douenne, 2020). However, when considering human psychology, an impartial planner must recognize that the gains of some do not compensate for the losses of others, as individuals are much more sensitive to a loss in standard of living than to an improvement (Kahneman & Tversky, 1979). In addition, it is difficult to offset these horizontal distributional effects through cash transfers without jeopardizing the incentive effect of the tax and thus the abatements it generates. Moreover, even if these disparities in the effects on purchasing power simply reflect the polluter–pays principle for people with different carbon footprints, them unfair in that individuals are penalized because of choices for which they are not responsible, particularly regarding investments decided at a time when greenhouse gas emissions were not part of the decision-making criteria (thermal boiler, suburban housing, car, etc.). Of course, by 2040 people have time to change their lifestyles : to move to a smaller home closer to their workplace, to insulate their dwelling or to install a heat pump. The time needed for these adjustments is actually an argument for delaying the tax's entry into force, since the tax already produces effects in anticipation as long as its long-term price trajectory is defined and credible. But very often, however,

26. It should be noted that, while a simple tax is easy to administer as it only concerns a few producers at the source of emissions (oil companies, cement factories, etc.), the precise evaluation of the emissions embodied in a product (i.e. its "carbon footprint") is only possible with detailed data on each company's supply chain : to this end, it would be useful to record all company purchases and sales in a global register.

households find themselves in a situation of dependence on fossil fuels because the alternatives are non-existent or unaffordable. Tenants do not have control over the insulation or boiler of their homes, while banks are reluctant to provide financing solutions to owners who would like to pay for the work through energy savings ; public transport is too infrequent or insufficiently served to replace individual cars in rural and peri-urban areas ; roads generally do not offer bicycle paths ; etc.

Also, as the public authorities are responsible for spatial planning and can finance long-term projects with a high social return even if they are risky in the short term and not very profitable, it is desirable that they finance low-emission equipment : public transport, thermal renovation, renewable energies, etc. Insofar as these investments are financed by a contribution from the richest and benefit disproportionately the poorest (this is often the case for public transport), their distributive effect is preferable to that of a carbon tax. Such investments, like any alternative abatement policy, make it possible to lower the level of carbon tax required to achieve a given emission reduction. And their distributional effects often justify lowering the carbon tax in this way, because even if it deviates from the cost-minimizing solution, the costs are distributed more equitably (Stiglitz, 2019). The same logic also applies to the overtaxation of products disproportionately used by the richest, such as kerosene or sports cars. Moreover, "green" investments can be advantageously financed by public debt (or monetization), especially in a context such as ours where many people are looking for work.[27] Indeed, in a context where production is below its full potential, the fiscal multiplier is greater than 1 : it was estimated at around 1.5 during the Great Recession (Blanchard & Leigh, 2013). This means that the public deficit generates more activity than it commands, ensuring the sustainability of public debt. Moreover, in a context of low inflation and interest rates persistently close to 0, there is no reason to worry about the consequences of an increase in inflation or public indebtedness (as long as the latter remains sustainable) (Blanchard, 2019). Finally, even if the fiscal multiplier were less than 1 in general, it might be higher than 1 in the case of green investment. Indeed, some papers show that green investment stimulates employment, as it involves sectors with a higher proportion of low-wage earners than average, a higher share of wages in the value added and (but less importantly) a more favorable trade balance (Bovenberg & van der Ploeg, 1994; Perrier & Quirion, 2018). In France, 630,000 jobs would thus be created by 2030 in a full decarbonization scenario (Quirion, 2013), and comparable results are expected in most countries (Bovenberg & Van der Ploeg, 1998; Ortega et al., 2015; Jacobson et al., 2017). This prospect of a demand stimulus through ecological transition is also what underlies the "Green Deal" or "Green New Deal" proposals on both sides of the Atlantic (Elliott et al., 2008; UNEP, 2009; DiEM25, 2017; Pacte Finance-Climat, 2018; Ocasio-Cortez, 2019; European Commission, 2019).

Various other deviations from the "standard model" justify climate policies other than a carbon tax alone. The introduction of standards or even bans is justified on products with several functionally equivalent versions, when (against all economic logic) consumers do not buy the most energy-efficient version : this is the case for light bulbs, for example (Stiglitz, 2019). Also, since innovations in "green" technologies benefit everyone, not just their inventor (after a few years, even competitors can use them), the private sector invests less in research and development than would be optimal for society (Acemoglu et al., 2012). The public sector can then compensate for this under-investment by subsidizing "green" innovation or by imposing standards that force the

27. In the fourth quarter of 2019, there were 2.4 million unemployed in France in the ILO sense and 1.7 million people in the halo around unemployment (looking for work but inactive in the ILO sense), cf. insee.fr/fr/statistiques/4309346.

private sector to innovate, such as vehicle emission standards (EPA, 2010; Reynaert, 2014; Klier & Linn, 2016). Finally, vehicle emission standards can also be justified in another way : to the extent that a certain status is conferred on a motorist by vehicle characteristics (such as weight) directly related to its emission intensity (Johansson-Stenman & Martinsson, 2006; Carlsson et al., 2007), it is appropriate to tax polluting vehicles above the usual rate (Howarth, 1996) or, equivalently, to impose penalties for any emission intensity in excess of a standard. More specifically, this justification is valid if the measure in question does not have an unfavorable distributive effect and if it reduces the over-consumption of polluting vehicles induced by their positionality (i.e. their status effect) or shifts it to other less polluting positional goods (such as electric cars, art pieces, or philanthropy).

Identifying obstacles to a decarbonized society

An ideal decarbonization program would therefore contain different measures targeting as many specific problems, structured around a carbon tax with dividend to align the choices of the whole society with the climate objective. But a key question remains : are people ready to shake up their lifestyles (taking little air travel, eating little meat, etc.) ? It is by no means obvious that a majority accepts these measures, even though they were designed to financially compensate the greatest number. This requires that most voters understand the climate issues, support the emission reduction targets, agree with the justifications for the proposed measures, and trust the government to implement them. These conditions are not obvious, especially since the effects of different measures are uncertain for anyone : for example, who can predict how the value of their house will be affected by decarbonization and the new land use planning it implies ? Loss aversion encourages the inaction of the status quo in such situations of uncertainty (Stiglitz, 2019).

In addition to this obstacle of decarbonization due to political acceptability, a potential physical limit drew my attention when I thought about these issues. Would an energy system based solely on renewables be viable and efficient ? While plans for transforming the energy system to all-renewable have been proposed, they neglect the energy cost of building the energy system itself. Or rather, they consider that a wind turbine or solar panel will require as much energy to be manufactured in a carbon-free world as it does today. However, it appears that the manufacture of wind turbines or solar panels requires more energy than that of thermal power plants (Weißbach et al., 2013). Therefore, if wind turbines and solar panels are manufactured using electricity from renewable sources rather than fossil fuels, the energy required (throughout the supply chain) for their manufacture increases. It is therefore crucial to know whether or not this effect compromises the efficiency of renewables in providing energy.

Finally, another obstacle to a decarbonized civilization is that it still relies on finite resources : metals. Indeed, no industry would be possible without metals, and this is particularly true for renewable energy production, which is very metal-intensive (Hertwich et al., 2015). However, when we consider the phenomenal energy that would be required to recover at the end of their life all the metal that made up our products (some of which has been dissipated into the environment and some of which is diluted in alloys), it is plausible that this energy exceeds the energy we can deliver by building power plants from this metal. This means that a strictly circular industrial metabolism is impossible, and that recycling will necessarily be partial. Admittedly, in practice, recyclability and mining resources may be high enough to ensure that humanity will not run out of metal for millions of years, but there is no guarantee of this. On the contrary, some experts predict a peak in copper mining by the middle of the 21st century and predict depletion of the resource within two centuries (Gordon et al., 2006; Henckens et al., 2014; Kerr, 2014; Sverdrup et al., 2014). While these alarmist predictions use an unduly narrow definition of what constitutes a copper resource, even the more optimistic estimates suggest that the resource will be depleted within a few thousand years (Kesler & Wilkinson, 2008). [28]

My thesis work consisted in analyzing these three obstacles to the emergence of a sustainable decarbonized society.

28. It is therefore legitimate to assume partial recyclability and finite resources, and to consider the optimal timing of extraction for energy production, given the availability of metal and fossil hydrocarbons. If we consider that humankind will live indefinitely, then the problem is ethically insoluble (because a finite resource cannot be divided into an infinite number of shares). But since there is a positive probability of extinction in each period, it is justified that the first generations exploit the resource in a reasoned way.

Summary

Both the disastrous impacts of unmitigated climate change and the depletion of fossil fuels call for a transition towards a decarbonized energy system. In this thesis, I wonder if and how such an energy transition can be achieved, and I study aspects of both its physical feasibility and political acceptability.

Almost each chapter falls within the economic literature and borrows methods from economics (intertemporal welfare maximization, instrumental variables estimation, representative surveys, input-output analysis...), while being at the same time linked to another discipline (industrial ecology, mathematics, behavioral studies or political science). Despite a common motivation to understand the conditions for the energy transition, each chapter is a stand-alone autonomous from the others.

While fossil fuels should be substituted by metals as the main inputs of energy collection, I show in Chapter I that it has never been established that such an energy transition would be physically sustainable, in the sense that a decarbonized electricity sector would deliver a net energy surplus to society. Indeed, the capacity to deliver an energy surplus is not an intrinsic property of a technology, as it depends on the whole chain of production. Thus, one cannot infer energy surpluses in a decarbonized scenario from the sole measure of *current* energy surpluses. I fill the gap in the literature and predict that the global efficiency of the electricity sector at delivering energy should be reduced by half in a 100% renewable scenario. I conclude the analysis by studying the link between energy prices and efficiency (defined as the Energy Returned On Invested).

As energy from fossil and renewable sources will coexist during the transition, and assuming that metal resources (necessary to collect renewable energy) are finite, it is interesting to know the optimal timing of extraction of fossils vs. metals. In Chapter II, which is a joint work with Mouez Fodha and Francesco Ricci, we answer this question and emphasize the importance of the recyclability of metals. We find that the higher the recycling rate, the sooner the transition towards renewables should take place, even without any pollution from fossils.

The rigorous demonstration of the optimality of the solution to our convex optimization problem appeared tedious (and required more than 10 dense pages), because we could not apply the Karush-Kuhn-Tucker theorem to our infinite horizon setting. It surprised me that this theorem, widely used by economists, had no extension to a countable (infinite) number of variables, so I started a collaboration with the mathematicians Mohammed Bachir and Sebastián Tapia García. In the Appendix D to Chapter II, we derive conditions for optimality and Gateaux differentiability of convex functions in certain spaces of infinite dimension (Banach spaces with a Schauder basis). The Karush-Kuhn-Tucker theorem naturally extends to the case of a convex function with a countable number of variables (such as series) and a finite number of constraints. Thus, under minimal hypotheses, a solution to first order conditions of an infinite horizon Lagrangian is necessarily an

optimum.

After a first part of the thesis that dispelled doubts as to the physical feasibility of a transition to renewable energies and helped to understand the interplay between energy, metals and recyclability, the irruption of the Yellow Vests movement was a sign that the limiting factor of decarbonization is its political acceptance. In the second part of the thesis, I therefore study the political constraints on decarbonization, i.e. the beliefs and preferences that allow or prevent the mitigation of climate change.

In a joint work with my friend and colleague Thomas Douenne, I investigate the climate policies that French people support by conducting an on-line survey on a representative sample of three thousands people. In Chapter III, we disentangle beliefs from preferences over a carbon tax and dividend scheme, which is praised by many economists as a cost-effective and progressive policy to tackle climate change and achieve the energy transition. We find that if 70% reject carbon taxation, it is mainly driven by pessimistic perceptions about the properties of the policy : in contradiction with our simulations, most think their household would lose purchasing power with the reform, which they perceive as regressive and ineffective to reduce pollution and fight climate change. The pessimism in beliefs cannot be easily corrected by providing new information to the respondents, as only a minority correctly update their responses. However, these compliers allow us to identify a robust causal effect where previous literature only showed correlations : acceptance of the reform increases by about 50 percentage points when one believes not to lose from the reform or when one believes in its environmental effectiveness. If the rejection of the carbon tax results from pessimistic beliefs about its properties that can be linked to a mistrust of the State, we also contribute to the literature on the formation of political beliefs by showing that these pessimistic beliefs could stem, through *motivated reasoning*, from a gut rejection of the measure, that we call *tax aversion*, and which can be rationalized by social psychology.

In a companion paper, constitutive of Chapter IV, we study the relationship of the French to climate change and climate policies in general. We elicit knowledge, perceptions and values over climate change, we examine opinions relative to carbon taxation, and we assess support for other climate policies. Among many results, we find limited knowledge but high concern for climate change, and we document a majority support for stricter norms and green investments. We find that knowledge about climate change increases concern about climate change, suggesting that better access to science could foster support for climate policies. Finally, one's position relative to the Yellow Vests appears the best predictor of environmental preferences, better than the traditional left-right spectrum.

Chapter I

Is renewable electricity sustainable ? Evolution of EROIs until 2050 [1]

Abstract The EROI –for Energy Returned On Invested– of an energy technology measures its ability to provide energy efficiently. Previous studies draw a link between the affluence of a society and the EROI of its energy system, and show that EROIs of renewables are lower than those of fossil fuels. Logically, concerns have been expressed that system-wide EROI may decrease during a renewable energy transition. First, I explain theoretically that the EROIs of renewables themselves could then decrease as energy-efficient fossil fuels would be replaced by less energy-efficient renewables in the supply-chain. Then, using the multiregional input-output model THEMIS, I estimate the evolution of EROIs and prices of electric technologies from 2010 to 2050 for different scenarios. Global EROI of electricity is predicted to go from 12 in 2010 to 11 in 2050 in a business-as-usual scenario, but down to 6 in a 100% renewable one. Finally, I study the economic implication of a declining EROI. An inverse relation between EROI and price is suggested empirically, even though theory shows that both quantities may move in the same direction.

Code All the code is on-line, and can be accessed from a notebook at : bit.ly/future_eroi_code. A substantial share of this work has been to contribute to the python library *pymrio* : github.com/bixiou/pymrio. Using my fork of pymrio, one can now easily undertake EROIs and related computations on Exiobase and THEMIS.

1 Introduction

As the harmful impacts of climate change call for a prompt energy transition away from fossil fuels —not to mention their depletion that shall ultimately make this transition unavoidable, concerns have been expressed that, in a decarbonized energy system, the lower efficiency of renewable energy might not allow sustaining advanced standards of living (Lambert et al., 2014;

1. *Ecological Economics*, 2019.

Tverberg, 2017).[2] We measure the energy efficiency of a technology or energy system using the Energy Returned On Invested (EROI), which is the ratio between the energy it delivers throughout its lifetime and the energy required along the chain of production to build, operate and dismantle it. A minimal requirement for a technology or energy system to be energetically sustainable is to have an EROI above 1, meaning that it provides more energy than it requires.

One issue to assess future energy systems is that the future EROI of a given technology cannot be readily deduced from current estimates. Indeed, as King (2014) remarked, the EROI of a technology is not intrinsic, but depends on the whole technological structure of the economy. Indeed, suppose that solar panels have a lower EROI than thermal power plants, so they require more energy to supply the same amount of energy. Then a plant producing solar panels will require more energy if the electricity it uses is produced by solar panels rather than by thermal plants. Ultimately, solar panels built using electricity from solar panels rather fossils will require more energy, and have a lower EROI. Some have called to compute the evolution of EROIs during a renewable energy transition (Brandt, 2017), and this study aims to do so while accounting for their system dependency. Indeed, provided that EROIs of renewables are lower than EROIs of fossils and that decreasing EROIs jeopardize prosperity, the evolution of EROIs during the energy transition is of critical importance : let us review these two hypotheses in turn.

Many estimations of EROIs have been made, and among the various different figures derived from diverse data sets and methodologies, none stands out as singularly authoritative, as shown by the controversy between Raugei (2013) and Weißbach et al. (2014). Still, Dale (2010) reviews all EROI estimates until 2010, while Hall et al. (2014) aggregate the estimates of the literature in a meta-analysis, and King & Bergh (2018) provide the likely ranges of electricity EROIs. Weißbach et al. (2013) is one of the few papers that computes the EROIs of different technologies in a comparable manner. The *buffered* EROIs of Weißbach et al. (2013) take into account the supplementary capacity, grid and storage required for the deployment of renewable technologies, which yields lower but presumably more accurate estimates for their EROIs. As anticipated, the EROIs of renewable electricity sectors they find are significantly lower than those of electricity from fossil fuels, except for hydro.

Some authors argue that the value of EROI is of primary concern, as they draw a link between the system-wide EROI and affluence of a society (Hall et al., 2009; Hall, 2011; Lambert & Lambert, 2011; Lambert et al., 2014; Fizaine & Court, 2016). Here is how Hall (2011) summarizes the argument :

> Think of a society dependent upon one resource : its domestic oil. If the EROI for this oil was 1.1 :1 then one could pump the oil out of the ground and look at it. (...) Hall et al. (2009) examined the EROI required to actually run a truck and found that if the energy included was enough to build and maintain the truck and the roads and bridges required to use it (i.e., depreciation), one would need at least a 3 :1 EROI at the wellhead. Now if you wanted to put something in the truck, say some grain, and deliver it that would require an EROI of, say, 5 :1 to grow the grain. (...) 7 or 8 :1 to support the families. If the children were to be educated you would need perhaps 9 or 10 :1, have health care 12 :1, have arts in their life maybe 14 :1 and so on.

The reasoning of Hall relies on the observation that all sectors of the economy require energy, and

2. The energy expert Jean-Marc Jancovici also expressed concerns over this subject during a presentation at the École Normale Supérieure in 2018 : "What happens to the EROI when you have only wind and solar panels to build wind and solar panels ? I think it crashes."

that the more efficient is the energy production (i.e. the higher is the EROI), the more energy is available to the rest of the economy. In strict logic, Hall's argument relies on two questionable assumptions : that factors of production (and especially the labor force) are used at their full capacity, and that technical and organizational progress will not be sufficient to sustain current level of prosperity with significantly less labor (or other factors of production in limited supply). If one rejects these assumptions, one can imagine a sustained level of prosperity with a lower system-wide EROI, provided that a higher share of factors of production be devoted to the energy sector : for example, unemployed people could be mobilized to sustain the energy surplus available to the rest of society. In parallel to a shift in the labor force, Raugei (2019) explains that an increased efficiency of energy use may also counteract the decrease in energy services implied by a declining EROI. That being said, given that current system-wide EROI is already declining due to the decline in fossil fuels quality (Dale et al., 2011; Poisson et al., 2013; Court & Fizaine, 2017) and that technical progress is incremental, the aforementioned analyses should not be neglected. Under the current system of production, which will persist in the short term, EROI should not decrease too much for prosperous standards of living to be sustained.

In view of the potential implications of a declining EROI, this paper provides an assessment of the EROI of different electricity technologies in various prospective scenarios, which includes a 100% renewable electricity system. To this end, I employ input-output analysis and I rely on a prospective series of multi-regional Input-Output Tables (IOT) : THEMIS (Gibon et al., 2015), which models two scenarios from the International Energy Agency (IEA, 2010) : Baseline and Blue Map. In addition, I modify THEMIS' IOTs to embed two decarbonized scenarios of power generation : Greenpeace's Energy [R]evolution (ER) and Advanced Energy [R]evolution (ADV) (Teske et al., 2015). Although Pehl et al. (2017) and Arvesen et al. (2018) already computed energy requirements of electricity technologies for prospective scenarios, they focused on life-cycle assessment coefficients such as future CO_2 emissions, and did not provide results in terms of EROI, let alone system-wide EROI. Furthermore, they did not study a scenario with 100% renewable electricity. I intend to fill this gap.

Then, I analyze the economic implications of a declining EROI through its relation with price. Previous studies suggest an inverse relation between EROIs and energy prices, and such an average relation is retrieved empirically using prices observed and predicted from THEMIS. However, theoretical analysis tempers this finding. Indeed, while explaining to what extent EROI and price are related, I show that they do not necessarily move in opposite directions. This calls for taking prices predictions from input-output analysis with more caution than EROI estimates, because IOT is better suited to handle physical notions than economic ones. Finally, the economic analysis weakens the view that a decrease in EROI would necessarily lead to a surge in energy expenditures and hence to a contraction of GDP.

Section 2 explains theoretically why the EROI of a technology is not an intrinsic property ; section 3 presents the methodology and the results ; section 4 studies the implications of declining EROIs on prices and GDP ; section 5 concludes.

2 The EROI of a Technology Is Not Intrinsic

2.1 A Simple Model With A Unique Energy Technology

The element $a_{i,j}$ of the technology matrix A represents the quantity of input i required to produce one unit of output j. Below is an illustrative technology matrix with three inputs (and the same three outputs) : an energy technology, materials, and energy. m_e denotes the quantity of materials (m) required to produce one unit of energy technology (e), and this notation extends naturally to all elements of A. The numerical values of the coefficients have a purely pedagogical purpose and have been arbitrarily chosen.

$$A = \begin{pmatrix} 0 & 0 & 1 \\ m_e & m_m & 0 \\ E_e & E_m & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ m_e & 0.2 & 0 \\ 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{energy techno.} \\ \text{materials} \\ \text{energy} \end{matrix}$$

The system-wide EROI, or Energy Returned On Invested, is the ratio between the energy delivered by the system, and the energy required in all stages of the chain of production to build, operate, maintain and dismantle it. In other words, it is the inverse of the amount of energy required to produce one unit of energy, when the series of all embodied inputs are taken into account.

The embodied inputs x required for a final demand y can be calculated using the Leontief inverse matrix (Leontief, 1986; Eurostat, 2008; Miller & Blair, 2009) :

$$x(y) = (I - A)^{-1} \cdot y. \tag{2.1}$$

We denote by $Drive/Thse/"udsrom.fd"\mathbb{1}_S$ the vector with 1 at the positions of the sectors $s \in S$, and zeros everywhere else. As energy E is the last input of our list, $\mathbb{1}_E = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ and the gross embodied energy required for a final demand y is the last element of x :
$\mathbb{1}_E^T \cdot (I_n - A)^{-1} \cdot y$. Thus, the EROI is

$$\begin{aligned} \text{EROI} &= \frac{\text{delivered energy}}{\text{net embodied energy}} \\ &= \frac{1}{\mathbb{1}_E^T \cdot \left((I - A)^{-1} \cdot \mathbb{1}_E - \mathbb{1}_E \right)}. \end{aligned} \tag{2.2}$$

After some calculations (available on-line), we find :

$$\begin{aligned} \text{EROI} &= \frac{(1 - E_e)(m_m - 1) + E_m m_e}{E_e (m_m - 1) - E_m m_e} \\ &= \frac{0.72 - 0.5 m_e}{0.08 + 0.5 m_e} \end{aligned} \tag{2.3}$$

Unsurprisingly, one can see in Figure 2.1 that the EROI decreases with the material intensity of the energy technology, because extracting and processing material requires energy.

For an intensity above 0.6, the EROI is below 1. An EROI below 1 means that the energy technology is not worth developing, because (in net) it consumes energy rather than providing

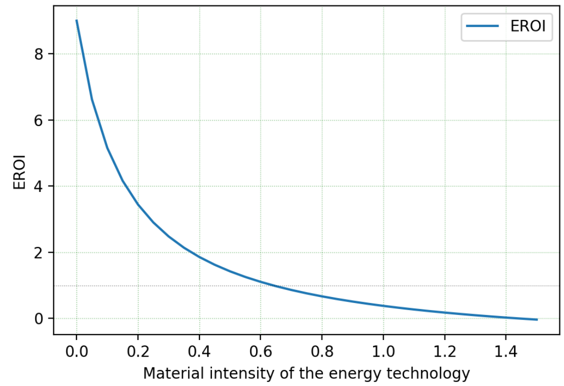


FIGURE 2.1 – EROI in the simple model in function of the material intensity m_e of the energy technology.

it. Such a system is not sustainable (and not realistic) : for it to happen the society should have accumulated energy in the past from an energy source no more accessible, and would waste this energy in that absurd technology.

For even higher intensities, the EROI falls below 0, which means that the energy (recursively) required to produce one unit of energy is infinite. Here, free energy coming from the past would not suffice to build the energy technology : one would also need to have free materials (i.e. materials requiring no energy to access them). Such a world is physically impossible.

2.2 A Simple Model With A Mix of Two Energy Technologies

Now, let us consider two energy technologies, with the same energy intensity, but different materials intensities.

Even if this example is purely illustrative, let us call them PV (for solar photovoltaic) and gas (for gas power-plant electricity) to grasp the motivation for this paper. The numbers are completely made up, but they respect the fact that PV is more material intensive than gas (Hertwich et al., 2015). Here is our new technology matrix, where p represents the share of PV in the energy (or electricity) mix.

$$A = \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ m_{PV} & m_g & m_m & 0 \\ E_{PV} & E_g & E_m & 0 \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ 0.7 & 0.1 & 0.2 & 0 \\ 0.1 & 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{PV} \\ \text{gas} \\ \text{materials} \\ \text{energy} \end{matrix}$$

With some calculus (see on-line), we obtain :

$$\text{EROI} = \frac{0.67 - 0.3p}{0.13 + 0.3p} \tag{2.4}$$

This corresponds to the system-wide EROI. But now that we have two technologies, we can compute the EROI of each of them : [3]

$$\begin{aligned} \text{EROI}_{PV} &= 1.558 - 0.698p \\ \text{EROI}_{gas} &= 5.154 - 2.308p \end{aligned} \tag{2.5}$$

Logically, the EROI of PV is lower as compared to gas because of its higher material intensity. But it is worth noticing that both EROIs depend on the energy mix p : the EROI of a technology is not an intrinsic property. Indeed, it depends on the whole economic system, or more precisely, of all technologies used in their chain of production. [4] Here, the higher the share of PV in the mix, the more the (lower) EROI of PV contaminates each technology, and the lower the EROI of both technologies.

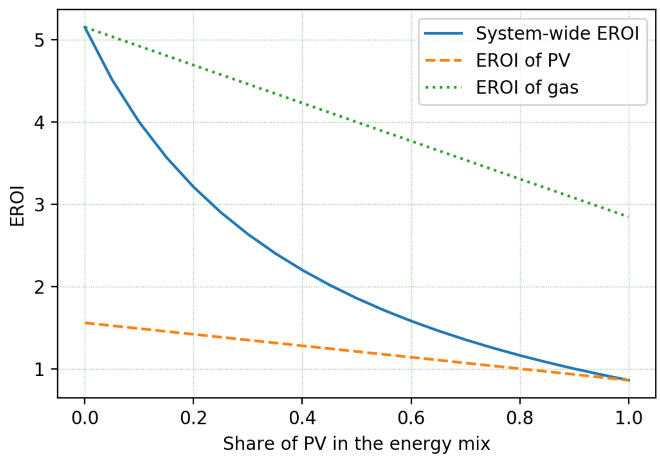


FIGURE 2.2 – EROIs in the two-technology model in function of the share p of PV in the energy mix.

One can see on Figure 2.2 that for highest penetration of PV, the EROI falls below unity. In other words, a renewable energy mix with 100% PV is not sustainable in this example. Even more worryingly, if one computes the EROI of PV in an energy mix relying mostly on gas, one would find a high-enough EROI for PV (meaning, above 1). Hence, one cannot conclude that a technology is sufficiently efficient (or sustainable) just by computing its EROI in the current energy mix. Yet, EROIs computations have always been done from actual data of our economy, and could falsely represent the efficiencies of energy technologies in another energy mix, say, a 100% renewable one. This uncertainty concerning the sustainability of a decarbonized energy system motivates the core

3. Similarly to the system-wide EROI, the EROI of a technology is the ratio between the energy delivered by one unit of this technology (over its lifetime), and the energy required to build, operate, maintain and dismantle it. Furthermore, one can show that $\frac{1}{\text{EROI}} = \frac{p}{\text{EROI}_{PV}} + \frac{1-p}{\text{EROI}_{gas}}$, and this formula generalizes to any number of technologies.

4. *Chain of production*, *recursive* or *embodied inputs* are synonyms ; their analysis is known as *structural path analysis* in the literature.

of this paper : the estimation of EROIs after a global energy transition.

It may go against the intuition that the EROI is not an intrinsic property of a technology : one could be tempted to picture the evolution of technological EROIs (the dotted lines in Figure 2.2) as flat, while only the system-wide EROI would be impacted by a change in the energy mix p. This constancy of EROI would hold if we did not account for embodied inputs in the definition of EROI, that is, if we included in the denominator only the energy used at the final stage of production of the energy technology (0.1 in our example). Yet, although definitions of EROIs vary among authors, such narrow definition for the system boundary is never adopted : indeed, this extremely narrow definition would not give an account of the ability for a technology to deliver a net energy surplus to society, thereby failing the *raison d'être* of the notion of EROI.

3 Estimation of Current and Future EROIs Using THEMIS

3.1 Definitions and Setting

Different notions of EROIs have been used in the literature, and some papers clarify them all (e.g. Brandt & Dale, 2011; Murphy et al., 2011). The most relevant notion for this research is defined by Brandt & Dale (2011) as the Gross Energy Ratio (GER). The GER measures the ratio of energy delivered over energy embodied in inputs net of the energy of the fuels transformed in the process (to avoid double-accounting). Thus, for example, the denominator of the GER does not take into account the energy provided by gas in a gas powered plant. The term "gross" is used because all energy output is taken into account ; on the contrary Net Energy Ratios subtract from the numerator all "self-use" output that is used in the pathway of production of the technology. [5] A related indicator that is sometimes used to compute EROI (as it is already included in many input-output databases) is the Cumulated Energy Demand (CED). I do not use it because Arvesen & Hertwich (2015) have shown that it is erroneous to use the CED directly for EROI computations, without making adjustments.

In most cases, EROIs (or energy ratios) are defined using quantities of primary energy. However, I adopt a different approach in this paper, and use only secondary energies in my computations. Indeed, as Arvesen & Hertwich (2015) put it, "EROI does not need to measure primary energy per se ; the crucial point is to measure energy diverted from society in a unit of equivalence". Also, the choice of secondary energy carriers is consistent with an energy system relying on renewable electricity, while for such systems the definition of primary energy is not harmonized and this can lead to inconsistencies : Frischknecht et al. (2015) spot for example a factor 6 between the cumulative (primary) energy demand for solar photovoltaic computed according to different methods. Although the sectors bringing energy are not the same in the two approaches (the primary approach uses crude oil when the secondary approach uses gasoline, for example), both approaches are equally valid.

Furthermore, practitioners often use a factor of conversion (around 3) to account for the higher

5. It is worth noting that the Gross Energy Ratio is called by King (2014) the net external energy ratio. As the terminologies of these two papers are not compatible, I follow Brandt & Dale (2011), who aim at harmonising the terminology. For King, "gross" energy is the total energy diverted from Nature while "net" is the output of energy from the technology, what Brandt and Dale call "gross". Furthermore, King would qualify "external" any notion that subtract the fuel transformed in production from the denominator, while Brandt and Dale always take this as a base case, and employ "external" when self-use output is also subtracted : it mirrors their notion of "net" for the denominator. As we study EROIs of electricity technologies, self-use output consists in electricity inputs in the pathway of production.

Table 3.1 – How this paper deals with classical problems of Net Energy Analysis

Problem	Reference	Solution adopted
System boundary	Suh (2004)	Input-Output (exhaustive) approach
Dynamic vs. steady state	Müller et al. (2014)	Steady state with vintage capital
Predicting future coefficients	Gibon et al. (2015)	Use of THEMIS modeling
Meshing distinct energy types	Raugei (2019)	Compare only electricity technologies
Primary vs. secondary energy	Arvesen & Hertwich (2015)	Secondary energy
Quality adjustment	Murphy et al. (2011)	Emphasis on non-quality adjusted, both done
Definition of EROI	Brandt & Dale (2011)	Gross Energy Ratio

quality of electricity as compared to fossil fuels. I follow the recommendation of Murphy et al. (2011) by undertaking my computations without and with a quality-adjustment factor of 2.6. However, I prefer not to bring to the fore the quality-adjusted computations, provided in Appendix C, and I focus instead on non-quality adjusted EROIs. The reason for this is that the factor of conversion is not well established : it represents the inverse of the yield of a thermal power station (about 38%), but this yield depends on the technology and on the fuel used. Moreover, for certain usage like heating, the yield of fossil fuels is close to that of electricity, and fossil fuels are disproportionately used for these applications for which they have a higher yield, therefore the difference in quality between fossils and electricity may be smaller than usually assumed. Finally, Table 3.1 summarizes the choices that have been made to address common problems in Net Energy Analysis. These choices are consistent with the method of Brand-Correa et al. (2017) to compute national EROIs.

To avoid the possible ambiguity of sentences, I reproduce below the formulas used to compute the EROI for a technology (or an energy system) t, which I denote GER_t^{2nd}. Let us recall that y is the vector of final demand, given by the scenario, and A is the technology matrix (or input-output table). E^S is the row vector of unitary energy supply per sector, meaning that E_t^S is the energy supplied by one unit of sector t, hence $E^S \cdot y_t$ gives the energy supplied by the technology t :[6]

$$\text{supply}_t = E^S \cdot y_t \tag{3.2}$$

$\odot$ (resp. $\oslash$) denotes the Hadamard (or entrywise) product (resp. division), so that $E^S \odot \mathbb{1}_{\text{2nd}}$ is the vector of unitary *secondary* energy supply. The main term at the denominator of the *GER* is the secondary energy embodied in inputs, net of the energy supplied by the technology :

$$\text{net embodied}_t = E^S \odot \mathbb{1}_{\text{2nd}} \cdot \left((I - A)^{-1} \cdot y_t - y_t \right) \tag{3.3}$$

To this term, we also need to subtract the energy supplied by secondary fuels which are direct inputs to thermal electricity somewhere in the supply-chain, including at the last stage. Indeed, such energy is not used to build or maintain the energy system ; rather, it is an energy transformed and delivered by the electricity technology, so including it would amount to double-counting. This term is especially important when t is some kind of thermal electricity.

$$\text{fuels inputs to elec}_t = E^S \odot \mathbb{1}_{\text{2nd fuel}} \cdot A \cdot \mathbb{1}_{\text{thermal elec}} \odot (I - A)^{-1} \cdot y_t \tag{3.4}$$

6. In practice, y is obtained from the scenario of energy demand from the IEA :

$$y_t = \left(\text{demand} \oslash E^S \right) \odot \mathbb{1}_t. \tag{3.1}$$

where $\mathbb{1}_{\text{thermal elec}} \odot (I - A)^{-1} \cdot y_t$ is the embodied thermal electricity.
Finally, we have :

$$GER_t^{2nd} = \frac{\text{supply}_t}{\text{net embodied}_t - \text{fuel input to elec}_t} \tag{3.5}$$

3.2 Data, Sources and Method

I apply these formulas to the IOTs (i.e. technology matrices A) and the vectors of unitary energy supply E^S from THEMIS (Gibon et al., 2015). THEMIS contains hybrid input-output tables : precise data on electricity units (the *foreground*) is completed with data on other sectors that originates from life cycle inventories and national accounts (the *background*). Gibon et al. (2015) have compiled various life cycle inventories into the 609 sectors of the foreground, including original and up-to-date life cycle inventories for electricity sectors. Hertwich et al., 2015 and its Supplementary Information (SI) detail sources and values retained for the evolution of crucial parameters of electricity technologies, such as energy efficiency and market shares of different photovoltaic modules. The background contains data in physical units for 4,087 sectors from the life cycle inventory ecoinvent and data in monetary units for 203 sectors from the input-output database Exiobase (Wood et al., 2014). The 44 Exiobase regions are aggregated into 9 macro-regions that coincide with those of the International Energy Agency (IEA), so that the number of rows and columns in each IOT is 9 times the number of sectors : 44,046. Starting from data of the 2010 IOT, the 2030 and 2050 IOTs of THEMIS embed expected technological efficiency improvements of key background sectors, produced by the New Energy Externalities Development for Sustainability project (NEEDS, 2009). NEEDS' realistic-optimistic scenario was identified as the closest match to the Blue Map and Greenpeace's scenarios assumptions, namely the deployment of the best available techniques and reasonable efficiency trends, while the realistic-pessimistic scenario matched the Baseline assumptions. Besides, improvements in foreground processes are modeled using (1) industry road maps, (2) technology learning curves, and (3) expert opinion (see SI of Hertwich et al. (2015) for more details). Furthermore, it is worth noting that THEMIS IOTs are constructed as if the whole economy were at a steady-state, contrarily to national accounts, which give the flows between sectors for a given year. This matches perfectly our purpose, because there is no need to adjust the EROI computations for the growth of some sector or for the lifetimes of some technologies. Finally, as THEMIS is multiregional, EROIs are given in total rather than internal terms, meaning that embodied energy contains energy embodied in imports. The two scenarios native in THEMIS are the baseline (BL) and the Blue Map (BM) scenarios of the IEA (IEA, 2010). While the former posits an almost constant electricity mix, the latter is compatible with a 50% probability to contain the global mean temperature anomaly to +2°C in 2100. As Blue Map still relies at 30% on fossil fuels based electricity in 2050 —including 17% with Carbon Capture and Storage (CCS) ; it does not allow assessing more decarbonized scenarios. Hence, I combine with THEMIS the scenarios from Greenpeace's Energy [R]evolution report (Teske et al., 2015). Greenpeace proposes a business as usual scenario (REF) close to baseline, as well as two scenarios compatible with the 2°C target. Both exclude CCS and phase out from nuclear between 2012 and 2050.[7] The first Greenpeace scenario, Energy [R]evolution (ER), comprises 93% of electricity

7. The study funded by Greenpeace was in fact conducted by researchers at the Institute of Engineering Thermodynamics of the German Aerospace Center (DLR), who applied their model REMix. Using the same model, Berrill et al. (2016) minimize the cost of European electricity generation under different carbon prices. Interestingly, an outcome of the model was to phase nuclear out, but to select coal with CCS. This indicates that the

from renewable sources in 2050, while the second one, Advanced Energy [R]evolution (ADV), attains 100% renewable. As the difference is small between these two scenarios, I focus on the 100% renewable one. I describe my methodology for embedding the regional electricity mixes of Greenpeace's scenarios into THEMIS in Appendix A.

In the literature, most EROIs estimations follow a bottom-up approach that use data from life cycle inventories. Bottom-up studies describe in details the power facilities and the most direct inputs to the energy technologies, but they do not cover the entire economy : indirect inputs such as clerical work or R&D are often beyond their system boundaries (Suh, 2004). On the contrary, the input-output method allows to encompass all embodied inputs exhaustively. As a consequence of this more comprehensive account of embodied energy than usual, we expect estimates of EROIs lower than the average of the literature. That being said, it is not a concern if our estimates are not directly comparable to those of the literature, as we are mainly interested in comparing them internally, among the different years and scenarios, and to scrutinize whether they vary substantially or not.

Because renewable sources are intermittent and dispersed, the capacity, grid extension and storage they require do not increase linearly with the electricity delivered. Hence, as Greenpeace scenarios are not native in THEMIS, they need further adjustments to account for these non-linearities. I explain in Appendix A how the need for overcapacity is addressed. Concerning transmission and storage, however, the requirements are not given by the Greenpeace report (Teske et al., 2015), so they have not been taken into account. Even if the report does not precise any plan relative to storage, hydrogen produced from renewables seems to play a substantial role in Greenpeace scenarios, as its share in the electricity mix is 5% in ADV 2050. However, as the sector 'Electricity from hydrogen' is absent from THEMIS, hydrogen has been excluded from this analysis. These limitations should be addressed in future work, together with the study of an energy transition in the transportation sector (which also partly relies on hydrogen). Such extension will not be easy, as the transportation sectors are still not sufficiently disaggregated in THEMIS to study a change in their technology. Meanwhile, other references can provide information on orders of magnitude of storage and transmission (Berrill et al., 2016; Koskinen & Breyer, 2016; Scholz et al., 2017). Applying REMix, the same optimization model that is used in the Greenpeace report, Scholz et al. (2017) show that the cost of storage and transmission combined is 4.6% of total cost in a business-as-usual scenario and 10.6% in a 100% renewable one. The adjustment needed for the cost, around 6%, gives a rough estimate of the upward bias of unadjusted EROI estimates (see section 4.2 on the relation between price and EROI).

Finally, data for Concentrated Solar Panels (CSP) had to be adjusted, because the original data mistakenly contained an energy supplied by unit of solar CSP of 0 in some regions (leading to abnormally low EROIs, around 2). Backed by Thomas Gibon, core developer of THEMIS, I corrected this error by setting the unitary energy supplied for solar CSP in all regions to its value in *OECD North America* (still letting the value depend on the scenario and the year).

3.3 Main Results

Main results are shown in Figure 3.1 and in Table 3.2. Complementary results for quality-adjusted EROIs and all scenarios can be found in Appendix C. Complete results are provided in the Supplementary Information spreadsheet : they include e.g. regional estimates and a decomposition

choices of Greenpeace were not solely motivated by a minimization of costs, but also by expert judgment and ethical considerations.

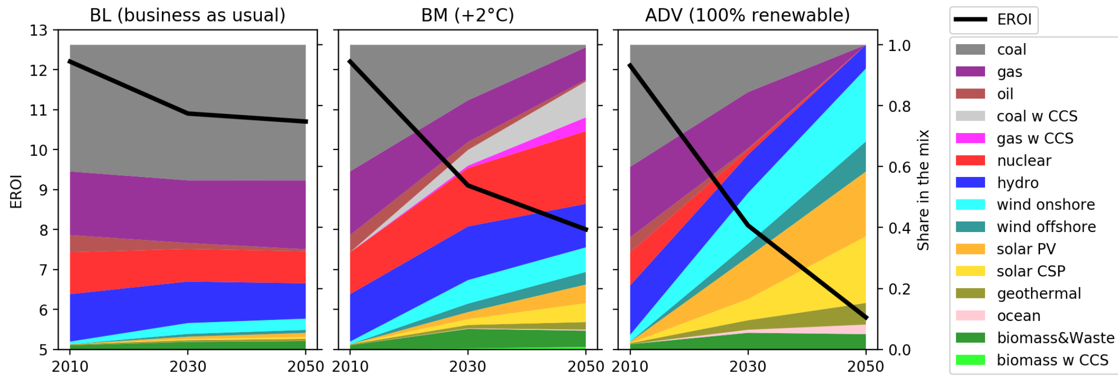


FIGURE 3.1 – Evolution of global EROIs and mixes of electricity for different scenarios.

of EROIs' denominators between direct and indirect energy. Some EROIs are missing, because not all technologies already existed on an industrial scale in 2010, and some technologies are discarded in the future by some scenarios. Conversely, some EROIs are given for apparent shares of production of 0 : this is the case when the share is rounded to 0, but not 0.

One can notice that, as expected, PV and wind panels have a lower EROI than electricity from fossil fuels. The EROIs of renewables decrease, as anticipated in the previous section. However, they remain largely above 1, suggesting that renewables are energetically sustainable. Recall that this was not evident as, *in theory*, nothing guarantees that EROIs stay above 1 when the energy mix changes (see section 2.2). Values for current EROIs range from 8 to 22. This range is in-line with that from Hall et al. (2014), but not with Weißbach et al. (2013), who find more contrasts between renewables and fossils. Such discrepancy is common in the EROI literature, may be due to differences in the methodology (Weißbach uses bottom-up data from specific locations) and does not affect this paper's results on the *evolution* of EROIs.

The system-wide EROI for the entire electricity sector is given at the bottom line of Table 3.2. It is estimated at 12.2 in 2010 ; it decreases slightly until 10.8 ± 0.1 in 2030 and 2050 in the Baseline scenario. An examination of regional estimates (see SI) reveals that this decrease is driven by a composition effect in the global mix. Indeed, the largest energy producer in 2010, North America, has higher EROIs and is replaced by China in 2030, which has lower ones ; the EROIs in each world region remaining quite stable.[8] The decrease is more pronounced when the penetration of renewable is higher : down to 8.0 in 2050 in the Blue Map scenario and even 5.8 in the 100% renewable one. The magnitude of the decline is substantial : an expected halving of global EROI may prove to be a challenge for the success of an energy transition to renewables.

One may wonder whether our results are driven by conservative forecasts concerning the progress in renewable technologies, or any other hypothesis concerning the evolution of the technology matrix. Of course, the quality of input-output data is never perfect, and making predictions is notoriously difficult, as was recently proven by the unexpected fall in the price of photovoltaic (PV) modules. However, there are several reasons to be more confident into future EROIs estimates from THEMIS than into past predictions on prices from other sources. First, technical coefficients are more stable than prices. Second, THEMIS accounts for materials and energy efficiency gains for electricity technologies, and uses "fairly favorable assumptions regarding wind conditions, in-

8. In Baseline, EROIs of *OECD Europe* and India are very close to global EROI, while those of Africa & Middle East and *Rest of developing Asia* are within ±3 to global ones.

Table 3.2 – EROIs and share in electricity mix of electric technologies in the model THEMIS for different scenarios and years.
The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	Baseline (BL)						Blue Map (BM, +2°)				ADV (100% renewable)			
Year	2010		2030		2050		2030		2050		2030		2050	
Variable	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix
biomass w CCS	–	0.00	–	0.00	–	0.00	4.6	0.00	4.0	0.01	–	0.00	–	0.00
biomass&Waste	11.4	0.01	6.3	0.02	5.9	0.03	5.5	0.06	5.2	0.05	5.2	0.05	4.6	0.05
ocean	5.5	0.00	2.4	0.00	2.9	0.00	3.7	0.00	5.8	0.00	4.8	0.01	4.9	0.03
geothermal	5.4	0.00	5.2	0.01	5.1	0.01	5.2	0.01	5.4	0.02	3.8	0.03	3.9	0.07
solar CSP	21.6	0.00	8.9	0.00	9.1	0.01	8.2	0.02	7.9	0.06	9.3	0.07	7.8	0.22
solar PV	9.3	0.00	7.4	0.01	7.2	0.01	6.4	0.02	6.0	0.06	5.4	0.14	4.7	0.21
wind offshore	9.4	0.00	11.0	0.01	10.5	0.01	7.7	0.03	6.3	0.04	6.5	0.04	6.4	0.10
wind onshore	9.5	0.01	9.3	0.04	8.1	0.04	7.1	0.08	7.3	0.08	7.2	0.17	5.8	0.24
hydro	13.2	0.16	11.9	0.14	11.9	0.12	12.8	0.18	13.1	0.14	11.0	0.13	10.9	0.08
nuclear	10.5	0.14	7.3	0.11	7.0	0.10	7.3	0.19	7.4	0.24	8.3	0.02	–	0.00
gas w CCS	–	0.00	–	0.00	7.5	0.00	7.9	0.01	9.1	0.05	–	0.00	–	0.00
coal w CCS	–	0.00	–	0.00	6.2	0.00	7.1	0.05	7.1	0.12	–	0.00	–	0.00
oil	8.4	0.06	9.8	0.02	9.9	0.01	9.5	0.03	7.3	0.01	10.0	0.01	–	0.00
gas	13.9	0.21	15.0	0.21	14.9	0.23	17.3	0.14	19.7	0.11	16.5	0.18	–	0.00
coal	12.9	0.42	11.5	0.45	11.5	0.45	11.6	0.18	12.4	0.01	10.4	0.16	11.5	0.00
Total	12.2	19.76	10.9	34.29	10.7	45.97	9.1	28.01	8.0	40.22	8.1	36.74	5.8	64.04

solation and resulting load factors", which if anything would bias EROIs of renewables upward (see SI of Hertwich et al., 2015). Third, THEMIS already includes recent industry road maps in its prospective matrices (see section 3.1), e.g. concerning the shift of PV market shares from cristalline silicon modules towards more efficient cadmium telluride (CdTe) or CIGS modules. Overall, the data from THEMIS seems most accurate concerning materials, metallurgy and energy sectors, and further improvements should probably focus on other sectors, like transport or services.

4 Implications of a Decreasing EROI on Prices and GDP

The forecast of declining EROIs made in the previous section calls for an assessment of its economic implications. The main channel through which a decrease in EROI could affect the economy is arguably a rise in energy price (and correlatively, in energy expenditures). In this section, I review the literature on the relation between EROI and the price of energy, estimate it empirically, and extend a result from Herendeen (2015) to characterize this relation. As in previous work, an inverse relation is documented empirically. Yet, theoretical analysis shows that EROI and price might decrease together. This theoretical result tempers the view that a decreasing EROI necessarily leads to a contraction of GDP.

4.1 Inverse Relation Proposed in First Studies

King & Hall (2011) point both theoretically and empirically that the price of a unit of energy p_t and the EROI of a technology t are inversely related. Defining the monetary return on investment MROI (i.e. the financial yield $\frac{\$_{\text{out}}}{\$_{\text{investment}}}$), they derive the formula :

$$p_t = \frac{\$_{\text{out}}}{E_{\text{out}}} = \frac{\text{MROI}_t}{\text{EROI}_t} \cdot \frac{\$_{investment}}{E_{\text{in}}} \tag{4.1}$$

TABLE 4.3 – Predicted average global price of electricity (in €/MWh)

year	2010	2030			2050		
scenario	all	BL	BM	ADV	BL	BM	ADV
price	27	28	30	30	28	30	32

Heun & de Wit (2012) find an equivalent formula. They designate MROI as the mark-up m_t, consider production costs per gross output $c_t = \frac{\$_{\text{investment}}}{E_{\text{out}}+E_{\text{in}}}$ and use their own notion of EROI : $\text{EROI}_t^H = \frac{E_{\text{out}}+E_{\text{in}}}{E_{\text{in}}} = \text{EROI}_t + 1$, so that equation (4.1) rewrites

$$p_t = \frac{m_t}{\text{EROI}_t^H - 1} \cdot \frac{\$_{\text{investment}}}{E_{\text{out}}+E_{\text{in}}} \cdot \frac{E_{\text{out}}+E_{\text{in}}}{E_{\text{in}}} = \frac{m_t \cdot c_t}{1 - 1/\text{EROI}_t^H} \tag{4.2}$$

The problem with these formulas is that all variables move together : when EROI varies, so does the cost of production, so that we cannot predict the future price taking this cost as fixed. Heun & de Wit (2012) acknowledge this ; and thus study the empirical link between EROI and price.

4.2 Empirical Relation Between EROI and Price

Using US data on oil and EROI from Cleveland (2005), Heun & de Wit (2012) regress p_t on the EROI. [9] They obtain a good fit even in their simplest regression ($R^2 = 0.8$), and find $p_{\text{oil}} = \beta_0 \cdot \text{EROI}_{\text{oil}}^{-1.4}$.

This result is interesting, and documents a negative relationship between price and EROI, which is close to an inverse one. As the authors do not regress price on the inverse of EROI, one cannot compare whether an inverse specification would provide as good a fit as a log-log one. To undertake this comparison, I run these two regressions using all estimates of EROI computed using THEMIS, one for each combination of scenario, year, region and sector. To obtain the price corresponding to each EROI, which I take *before* taxes and subsidies on production ; I assemble from the columns *compensation of employees* and *operating surplus* of the characterization matrix of THEMIS a row vector v of value-added per unit of each sector. Indeed, the vector of prices excluding tax p can be seen as emerging from value-added according to

$$p = v \cdot (I - A)^{-1} \oslash E^S \tag{4.3}$$

because the price of energy in sector s, p_s, is the sum of the value-added of inputs embodied in $s : v \cdot (I-A)^{-1} \cdot \mathbb{1}_s$, divided by the energy supplied by one unit of $s : E_s^S$. To the extent that the physical constituents and processes of a given technology will not change in an unexpected way, and as THEMIS models technical progress but not behaviors nor general equilibrium effects, prices forecast using the above formula might not be as reliable as EROI estimates. For this reason, I report only the global average electricity prices of the main scenarios (see Table 4.3), but I do not detail the substantial variations between regions or sectors. [10]

Table 4.4 reports the results of both the log-log and the inverse fits. I ran each model twice : first, on all 2079 positive observations available, and then on the 104 observations for year 2010. To make the R^2 of the log-log fit comparable to that of the inverse fit, I compute it as the sum of squared

9. Although they claim that their explained and explanatory variables are respectively the cost of production and their notion of EROI, EROI^H, the former is indeed the producer price and the latter our notion of EROI, according to the source of their data : Cleveland (2005).

10. The results are on-line and available on demand.

TABLE 4.4 – Regressions of price on EROI (both estimated using THEMIS).
All coefficients are significant at the 1‰ level.

Obs.	**N**	**Specification**	**Coefficients** a	b	R^2 [a]
All	2079	$p = \frac{a}{EROI} + b$	85	18	0.55
2010	104		72	21	0.54
All	2079	$\log(p) = a \cdot \log(\text{EROI}) + b$	−0.57	2.0	0.58
2010	104		−0.46	1.9	0.62

a. The R^2 given for log-log fits is not the original one, cf. text.

errors between "observed" prices and predicted prices (instead of their respective logarithms). As all R^2 are between 0.54 and 0.62, the inverse fit is almost as accurate as the log-log fit. Moreover, although the elasticity of price on EROI estimated here is different from that found by Heun & de Wit (2012) for oil (around −0.5 as compared to −1.4), both figures are close to 1. Empirical findings confirm an inverse relation between price and EROI. However, Figure 4.1 shows that a significant share of the variance in price remains unexplained by EROI, even more so for values of EROI around the global averages of 6-12, where the fit is almost flat and the errors substantial. In addition, theoretical analysis rejects the existence of a mapping between price and EROI.

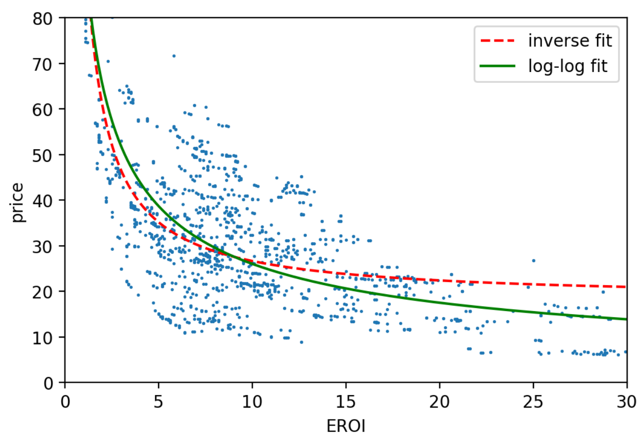


FIGURE 4.1 – Regressions of price on EROI (all observations, from THEMIS).

4.3 A Case Against Any Simple Relation

Herendeen (2015) shed new light on the theoretical relation by treating the question from its matrix form and introducing the concept of value-added. Herendeen showed how to express rigorously the price in function of the EROI when the economy is constituted of two sectors (energy and materials), and explained the limits of such exercise. Hereafter, I extend the results of Herendeen to an arbitrary number of sectors, n. His approach relies on the concept of *energy intensity*.

To deliver one unit of energy technology t, the production mobilized is $(I - A)^{-1} \cdot \mathbb{1}_t$, while the energy mobilized, called the energy intensity of t, writes $\varepsilon_t = \mathbb{1}_E^T \cdot (I - A)^{-1} \cdot \mathbb{1}_t$, where E is the set of all energies. [11] ε_t is in fact the gross energy embodied in t, i.e. the sum of the delivered and the net embodied energy. Hence, the EROI of t is a simple function of ε_t : $\text{EROI}_t = \frac{\mathbb{1}_E^T \cdot \mathbb{1}_t}{\mathbb{1}_E^T \cdot \left((I-A)^{-1} - I\right) \cdot \mathbb{1}_t} = \frac{1}{\varepsilon_t - 1}$.

In Appendix D, I show that the price of a technology t is a certain function of the coefficients of A, [12] and that each coefficient of A can be expressed as a function of EROI. Composing two such functions, we obtain that the price is inversely related to EROI. However, the relation is not unique (as it depends on the coefficient of A chosen to make the connection), and the other parameters in the relation are not constant. This leads to the following Proposition :

Proposition 4.1. *(Generalization of Herendeen, 2015) Assuming that all coefficients of the transformation matrix A are constant except one, noted $x = a_{i_0, j_0}$, and that EROI varies with x ; the price of t can be expressed as a linear function of its energy intensity $\varepsilon_t = 1 + \frac{1}{EROI_t}$, so that :*

$$\exists! \, (\alpha, \beta) \in \mathbb{R}^2, \; p_t = \frac{\alpha}{EROI_t} + \beta \tag{4.4}$$

Démonstration. See Appendix D. □

Remarque. With the terminology of Heun & de Wit (2012) or Herendeen (2015), the relation above would write :
$p_t = \alpha \frac{\text{EROI}_t^H}{\text{EROI}_t^H - 1} + \gamma$, with $\gamma = \beta - \alpha$. This is because in their definition of EROI, the numerator is ε_t instead of 1.

In the general case, we cannot obtain a *better* result, i.e. a formula that still holds when letting more than one coefficient vary. Indeed, denoting $\omega_{i,t}$ the coefficient (i, t) of $(I - A)^{-1}$, the Laplace expansion of $I - A$ gives us $\omega_{i,t} = \frac{(-1)^{i+j}}{\det(I-A)} \det\left(\left((I-A)_{j,k}\right)_{\substack{j \in [\![1;n]\!] \setminus i \\ k \in [\![1;n]\!] \setminus t}}\right)$. Hence, we have $\varepsilon_t = \sum_{e \in E} \left((I-A)^{-1}\right)_{e,t} = \sum_{e \in E} \omega_{e,t}$ and $p_t = \sum_{i=1}^n v_i \left((I-A)^{-1}\right)_{i,t} = \sum_{i=1}^n v_i \omega_{i,t} = \sum_{e \in E} v_e \omega_{e,t} + \sum_{i \notin E} v_i \omega_{i,t}$ Denoting $\tilde{v} = \frac{\sum_{e \in E} v_e \omega_{e,t}}{\sum_{e \in E} \omega_{e,t}}$ and $r = \tilde{v} + \sum_{i \notin E} v_i \omega_{i,t}$, we obtain

$$p_t = \tilde{v} \varepsilon_t + \sum_{i \notin E} v_i \omega_{i,t} = \frac{\tilde{v}}{\text{EROI}_t} + r \tag{4.5}$$

However, one has to keep in mind that r, $\tilde{v}$ and EROI_t all depend on the coefficients of A, and vary together when A changes. If there is only one type of energy ($E = \{e\}$) or if value-added is equal for all types of energy ($\forall e \in E, \, v_e = \tilde{v}$), $\tilde{v}$ does not depend on the coefficients of A anymore, and we obtain a formula close to that of King & Hall (2011) : $p_t = \frac{v_e}{\text{EROI}_t} + r$. Still, when the EROI varies because more than one coefficient of A changes, r varies concomitantly, and the EROI cannot be used as a sufficient statistic to infer the price. For this reason, one cannot identify empirically a linear relation between price and the inverse of EROI without strong assumption on the steadiness of A.

Actually, the theoretical relation between EROI and price is so fragile that one cannot even conclude that it is a decreasing relation : I provide in Appendix B a numerical example showing that EROI and price can both increase at the same time when more than one coefficient varies. Such acknowledgment dissuades from predicting long run prices by simply looking at estimations of future EROIs.

11. I assume here that the unit of an output of an energy sector $e \in E$, hence of $\mathbb{1}_E^T$, is an energy unit, like TWh.
12. More precisely, a function field of a certain algebraic variety.

Does this mean that EROI is unrelated to any economic concept ? Fizaine & Court (2016) argue that there is a minimum EROI below which the US economy enters a recession. They first show that energy expenditure Granger causes growth in the US, then determine a threshold of energy expenditure above which the US enters in a recession (consistent with that of Bashmakov, 2007), and finally use a modified version of equation (4.1) to relate this to a minimum non-recessionary EROI. However, they misleadingly replace the inverse of the energy intensity of energy investment $\frac{\$_{investment}}{E_{\text{in}}}$ by that of the whole economy, $\frac{GDP}{E_{\text{out}}}$. This prevents them from noticing that cost reductions in energy production could compensate the effect of a decreasing EROI on energy prices and expenditures, not mentioning improvements in efficiency and sobriety in usage. As we have seen, EROI, price and energy expenditure may all decrease at the same time, which undermines the idea that a recession caused by a surge in energy expenditure is ineluctable as soon as EROI goes below some threshold. In addition, an energy price increase should have an expansionary effect on net exporters of energy, at odds with the mechanism extrapolated by Fizaine and Court from the case of the United States, which has been historically a net energy importer. Overall, the analysis of this section indicates that the economic consequences of a change in EROI are ambiguous, and that this physical notion cannot be used to predict future prices or GDP without empirical evidence.

5 Concluding Remarks

This work includes a first attempt at estimating future EROIs in a decarbonized electricity system. By examining a broad range of scenarios, it concludes that the system-wide EROI of the power sector should decrease until 2050, from 12.2 to 10.7 in a business-as-usual scenario, 8.0 in a partial transition away from fossil fuels, or 5.8 in a scenario with 100% renewable electricity. Even though the EROI of each technology is expected to remain well above 1, which was questioned theoretically, our results show that renewable electricity is not as energetically efficient as previously thought.

As an inverse relationship between EROIs and energy prices is consistently found empirically, a declining EROI could mean higher energy prices. However, theoretical analysis of this relation showed that a declining EROI might also coincide with decreasing energy prices, and does not necessarily lead to a recession. Furthermore, the price increases predicted empirically remain modest (at most +20%) and could be accommodated through improved efficiency in usage.

Finally, this paper assessed scenarios of transition in the electricity sector, but further research is still needed to estimate future EROIs in complete energy transitions, which include a mutation of the transportation system, agriculture and industry. Unfortunately, this could not be done using the current version of THEMIS, and the question remains open for future research. Another goal for the field would be to converge on the methods to compute EROIs of renewables, notably on how to integrate buffering, i.e. overcapacity and storage requirements. Indeed, if EROIs of renewables were higher than those of fossils —which is sometimes found when buffering is not accounted for, e.g. in Raugei & Leccisi (2016)— then a decline in system-wide EROI would not even be a concern. Hence, defining common methodological principles would help to narrow the gap between estimates from different sources.

To conclude, as this article suggests that EROIs of renewables are lower than those of fossils, implying that global EROI would decrease substantially in a renewable energy transition, it is worth emphasizing that the choice to undergo a renewable transition – or not – should not be reduced to considerations of EROIs. Indeed, given the negative externalities and the scarcity of fossil fuels, a renewable transition is well justified.

Appendix

A Updating a Matrix *A* To a New Given Mix

The technology matrices A for the IEA scenarios are readily available in THEMIS, but these matrices have to be updated to the new electricity mix for the Greenpeace scenarios. To do this, I exploit the fact that both THEMIS and Greenpeace use the world regions of the IEA, and I modify the electricity input of each sector by the regional mix given by Greenpeace. The most accurate algorithm to update an input-output matrix is known as GRAS (Junius & Oosterhaven, 2003). Although I implemented this algorithm in pymrio ; I could not use it, because this algorithm uses the new sums of rows and columns to balance the matrix, and the vector of final demand y or the vector of production x is necessary to know them. As THEMIS does not include such vectors, I had to use a simpler method, which relies on the assumption that the electricity mix of inputs is the same across sectors for a given region. Given the perfect substitutability between electricity produced by different technologies and the uniqueness of electric grids, this assumption seems justified.

There are two different updates to make. First, I modify the vector of second energy demand (used to infer the final demand of technology t, y_t) so that it perfectly matches the demand of the scenario. Second, I modify the submatrix D of A containing the rows of electricity sectors. To convert D in energy units, I multiply each row t of D by the corresponding energy supplied per unit of technology t, E_t^S. I call the result E : the coefficient E_{is} of E gives the electricity from sector i required to make one unit of sector s' output, where $i = i\,(t, r)$ corresponds to technology t in region r. Then, I premultiply E by a block diagonal matrix with R blocks of size $T * T$ containing only ones (where $R = 9$ and $T = 15$ are the number of THEMIS regions and electricity sectors, respectively) to obtain a matrix B. Each row of B gives the total electricity from a given region r required to produced each output, E_r^{tot}, and each row E_r^{tot} is replicated T times :

$$B = \begin{pmatrix} B_1 \\ \vdots \\ B_R \end{pmatrix}, \quad B_r = \begin{pmatrix} E_r^{\text{tot}} \\ \vdots \\ E_r^{\text{tot}} \end{pmatrix}$$

Next, each row of B is multiplied by the share of a technology t in the mix of the corresponding region, which defines a matrix $\tilde{E}$. Each coefficient $\tilde{E}_{i,s}$ of $\tilde{E}$ gives the electricity from sector i required to make one unit of sector s' output, according to the new mix (by construction, for all electricity sector $j = i\,(t, r)$, the share of technology j in the regional mix, $\frac{\tilde{E}_{j,s}}{\sum_t \tilde{E}_{i(t,r),s}}$, is the same across all sectors s). Eventually, I obtain the new submatrix $\tilde{D}$ by converting each row of $\tilde{E}$ to the original units of A (by dividing each row by the appropriate unitary energy supplied E_t^S).

A last update is needed for Greenpeace scenarios, to account for the extra capacity needed when intermittent sources fail to deliver energy : the ratio of capacity (in GW) over production (in TWh) is somewhat higher in Greenpeace scenarios than in IEA/THEMIS ones. Thus, I multiply each column of an energy sector (representing all inputs required for one unit of output of this sector) by the ratio of the capacity-over-production ratios of Greenpeace and IEA/THEMIS. Doing so relies on the fact that the energy required to operate a power plant is negligible in front of the energy required to build it (see e.g. Arvesen et al. (2018)).

B Example of Non-Decreasing Relation Between EROI and Price

Herendeen (2015) proposes a calibration on US energy data of his toy model with 2 sectors (materials and energy), which yields as realistic results as a two-by-two model can yield. I start from a slightly modified version of his calibration (called *base*), in the sense that the figures are rounded, and I show how a deviation of two coefficients (in the *new* calibration) leads to an increase of both EROI and price of energy. This proves that in general, nothing can be said of the relation between EROI and price, not even that it is a decreasing relation.

For this, I use the formulas for EROI and price given by Herendeen (2015) (where I convert the price to \$/gal using the conversion factor 1 Btu = 114, 000 gal) :

$$\text{EROI} = \frac{1}{A_{ee} + \frac{A_{em}A_{me}}{1-A_{mm}}} \tag{B.1}$$
$$p = \frac{v_e\left(1-A_{mm}\right) + v_m A_{me}}{\left(1-A_{ee}\right)\left(1-A_{mm}\right) - A_{em}A_{me}} \cdot 114,000$$

Table B.1 – Example of sets of coefficients exhibiting a non-decreasing relation between EROI and price in a two sectors model (see desmos.com/calculator/ne4oqunhsm).

	base	**new**
v_m	0.5	
v_e	$5 \cdot 10^{-6}$	
A_{em}	1700	
A_{me}	$4 \cdot 10^{-6}$	
A_{mm}	0.5	0.9
A_{ee}	0.3	0.1
EROI	3.2	6.0
price	1.5	3.4

C Complementary Results

Results without quality adjustment for IEA/THEMIS scenarios are provided in section 3.3; those for Greenpeace's scenarios are in Table C.1. Quality-adjusted results follows in Table C.2 (IEA/THEMIS) and C.3 (Greenpeace). The quality adjustment consists in separating each energy in the formula of the EROI according to its origin (electric or thermal), and to weight electricity by a factor 2.6. For example, the quality-adjusted (gross) embodied energy for a unit of technology t writes

$$\text{embodied}_t^{\text{qual. adj.}} = E^S \odot \left(2.6 \cdot \mathbb{1}_{\text{electric}} + \mathbb{1}_{\text{thermal}}\right) \cdot (I-A)^{-1} \cdot \mathbb{1}_{\text{t}} \tag{C.1}$$

Table C.1 – EROIs and share in electricity mix of electric technologies in the model THEMIS for the Greenpeace scenarios.
The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**all**		**REF**				**ER** (+2°C, no CCS, no nuclear)				**ADV** (100% renewable)			
Year	**2012**		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
biomass&Waste	8.5	0.02	6.4	0.03	5.0	0.03	5.3	0.06	4.7	0.06	5.2	0.05	4.6	0.05
ocean	4.7	0.00	2.0	0.00	2.5	0.00	4.3	0.01	4.5	0.03	4.8	0.01	4.9	0.03
geothermal	5.6	0.00	3.8	0.01	2.5	0.01	3.6	0.03	3.7	0.07	3.8	0.03	3.9	0.07
solar CSP	35.5	0.00	9.3	0.00	8.0	0.01	8.5	0.05	7.7	0.17	9.3	0.07	7.8	0.22
solar PV	13.7	0.00	7.0	0.02	5.3	0.02	5.6	0.11	4.4	0.20	5.4	0.14	4.7	0.21
wind offshore	9.1	0.00	8.6	0.01	7.8	0.01	5.6	0.03	5.9	0.08	6.5	0.04	6.4	0.10
wind onshore	9.7	0.02	9.1	0.05	7.2	0.05	7.2	0.15	6.0	0.22	7.2	0.17	5.8	0.24
hydro	12.2	0.16	11.4	0.14	11.2	0.13	11.0	0.14	11.1	0.10	11.0	0.13	10.9	0.08
nuclear	12.2	0.11	7.3	0.10	7.1	0.08	8.3	0.02	–	0.00	8.3	0.02	–	0.00
gas w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
coal w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
oil	8.4	0.05	11.1	0.02	11.4	0.01	10.0	0.01	9.2	0.00	10.0	0.01	–	0.00
gas	14.9	0.23	15.3	0.23	15.6	0.25	16.6	0.21	17.2	0.06	16.5	0.18	–	0.00
coal	11.8	0.40	11.3	0.40	11.3	0.39	10.7	0.19	10.8	0.01	10.4	0.16	11.5	0.00
Total	12.1	22.60	10.7	36.26	10.1	50.11	8.4	33.60	5.9	49.20	8.1	36.74	5.8	64.04

Table C.2 – Quality-adjusted EROIs (with a factor of 2.6 for electricity) and share in electricity mix of electric technologies for IEA/THEMIS scenarios.
The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**Baseline (BL)**						**Blue Map (BM, +2°)**			
Year	**2010**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0.00	–	0.00	–	0.00	9.5	0.00	8.5	0.01
biomass&Waste	20.8	0.01	12.6	0.02	11.7	0.03	11.6	0.06	11.1	0.05
ocean	9.1	0.00	4.4	0.00	5.5	0.00	7.0	0.00	11.3	0.00
geothermal	11.5	0.00	10.3	0.01	10.2	0.01	10.6	0.01	11.4	0.02
solar CSP	44.6	0.00	17.7	0.00	18.2	0.01	17.3	0.02	16.9	0.06
solar PV	17.5	0.00	14.8	0.01	14.5	0.01	13.3	0.02	12.9	0.06
wind offshore	19.6	0.00	21.2	0.01	20.5	0.01	15.4	0.03	13.0	0.04
wind onshore	18.4	0.01	18.1	0.04	15.8	0.04	14.5	0.08	15.4	0.08
hydro	25.6	0.16	23.0	0.14	23.0	0.12	25.2	0.18	26.3	0.14
nuclear	19.2	0.14	13.4	0.11	13.0	0.10	13.6	0.19	13.9	0.24
gas w CCS	–	0.00	–	0.00	14.4	0.00	16.2	0.01	18.8	0.05
coal w CCS	–	0.00	–	0.00	11.7	0.00	13.7	0.05	14.3	0.12
oil	12.9	0.06	15.6	0.02	16.0	0.01	15.5	0.03	11.8	0.01
gas	22.5	0.21	24.6	0.21	24.4	0.23	29.0	0.14	33.5	0.11
coal	20.2	0.42	18.2	0.45	18.2	0.45	18.4	0.18	19.6	0.01
Total	20.4	19.76	18.7	34.29	18.4	45.97	17.0	28.01	16.0	40.22

TABLE C.3 – Quality-adjusted EROIs (with a factor of 2.6 for electricity) and share in electricity mix of electric technologies for Greenpeace scenarios.
The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**all**		**REF**				**ER** (+2°C, no CCS, no nuclear)				**ADV** (100% renewable)			
Year	**2012**		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
biomass&Waste	15.7	0.02	12.6	0.03	9.8	0.03	10.4	0.06	9.2	0.06	10.3	0.05	9.1	0.05
ocean	7.8	0.00	3.6	0.00	4.6	0.00	8.4	0.01	9.1	0.03	9.3	0.01	9.7	0.03
geothermal	12.1	0.00	7.6	0.01	5.0	0.01	7.2	0.03	7.3	0.07	7.6	0.03	7.7	0.07
solar CSP	73.2	0.00	19.1	0.00	16.1	0.01	17.6	0.05	16.1	0.17	19.0	0.07	16.2	0.22
solar PV	25.8	0.00	13.7	0.02	10.5	0.02	11.5	0.11	9.2	0.20	11.3	0.14	9.9	0.21
wind offshore	17.3	0.00	16.0	0.01	15.1	0.01	11.6	0.03	12.2	0.08	13.3	0.04	13.2	0.10
wind onshore	18.6	0.02	17.6	0.05	14.1	0.05	14.9	0.15	12.4	0.22	14.8	0.17	12.1	0.24
hydro	23.5	0.16	22.1	0.14	21.9	0.13	21.4	0.14	21.3	0.10	21.4	0.13	21.1	0.08
nuclear	22.8	0.11	13.6	0.10	13.3	0.08	16.4	0.02	–	0.00	16.4	0.02	–	0.00
gas w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
coal w CCS	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00	–	0.00
oil	12.8	0.05	17.8	0.02	18.2	0.01	15.9	0.01	13.3	0.00	15.8	0.01	–	0.00
gas	23.8	0.23	25.0	0.23	25.8	0.25	27.1	0.21	28.2	0.06	27.2	0.18	–	0.00
coal	18.6	0.40	17.8	0.40	18.0	0.39	16.6	0.19	16.6	0.01	16.2	0.16	15.3	0.00
Total (PWh/a)	20.1	22.60	18.5	36.26	17.7	50.11	15.9	33.60	12.0	49.20	15.5	36.74	11.9	64.04

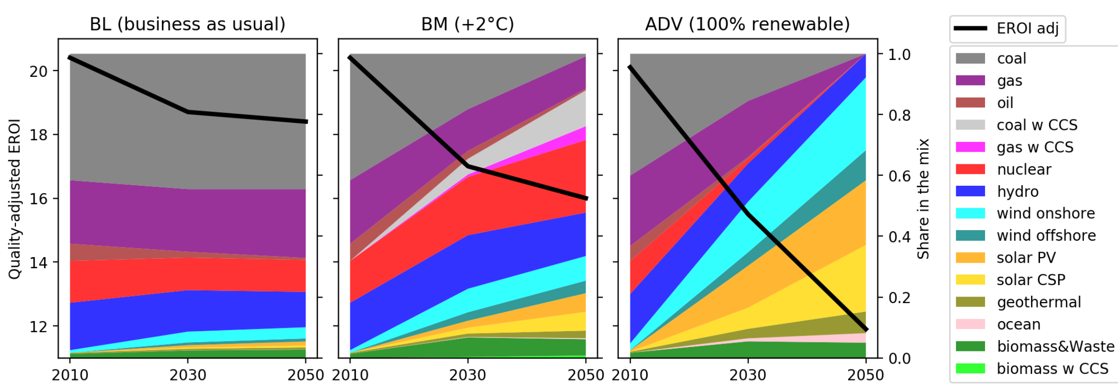


FIGURE C.1 – Evolution of global quality-adjusted EROIs (with a factor 2.6 for electricity) and mixes of electricity for different scenarios.

D Proof of Proposition 4.1

The demonstration starts with a lemma :

Lemme D.1. *Let A be an invertible matrix and let x be a coefficient of A. Then,*

(i) the determinant of A is a linear function of x, denoted D^A ;

(ii) each coefficient (i,j) of the adjugate of A is a linear function of x, denoted $P^A_{i,j}$;

(iii) each coefficient (i,j) of A^{-1} is a rational function in x of degree 1, which writes : $\left(A^{-1}\right)_{i,j} = \frac{P^A_{i,j}(x)}{D^A(x)}$.

Démonstration. Let $A = (a_{i,j})_{1\leq i,j\leq n} \in GL_n(\mathbb{R})$ an invertible matrix and let $(i_0, j_0) \in [\![1;n]\!]^2$ so that, without loss of generality, $x = a_{i_0,j_0}$. (i) From its definition by the Leibniz formula, the determinant of A writes $\det(A) = \sum_{\sigma\in S_n} \operatorname{sgn}(\sigma) \prod_{i=1}^{n} a_{i,\sigma(i)}$, where $\operatorname{sgn}(\sigma)$ is the signature of permutation σ and S_n the set of all permutations of n elements. In this linear combination, each term is a product containing x at most once, it is thus a linear function of x. (ii) A minor being the determinant of a submatrix of A, we know from (i) that it is a linear function of x (which reduces to a constant for submatrices that do not contain x). Each coefficient of the adjugate of A is (plus or minus) a minor of A, hence a linear function of x. (iii) Using (i) and (ii) and the Laplace expansion of A : $A^{-1} = \frac{\operatorname{adj}(A)}{\det(A)}$, we reckon $\left(A^{-1}\right)_{i,j} = \frac{P^A_{i,j}(x)}{D^A(x)}$. □

Démonstration. (Proposition 1) Defining $R(x) := D^{I-A}(\delta_{i_0,j_0} - x)$,
there is a unique linear function $P^{I-A}_{e,t}$ such that $\left((I-A)^{-1}\right)_{e,t} = \frac{P^{I-A}_{e,t}(\delta_{i_0,j_0}-x)}{R(x)}$, where $\delta_{i,j}$ is the Kronecker delta. As a linear combination of compositions of linear functions, the functions
$Q(x) := \sum_{e\in E} P^{I-A}_{e,t}(\delta_{i_0,j_0} - x)$ and $P(x) := \sum_{i=1}^{n} v_i P^{I-A}_{i,t}(\delta_{i_0,j_0} - x)$ are themselves linear. By definition, we have
$\varepsilon_t = \sum_{e\in E} \left((I-A)^{-1}\right)_{e,t}$, so that $Q(x) = \varepsilon_t R(x)$. As P, Q and R are linear, and as ε_t varies with x, it is easy to show that there are unique real numbers α and γ such that $P(x) = \alpha Q(x) + \gamma R(x)$. Finally, observing that $p_t = \sum_{i=1}^{n} v_i \left((I-A)^{-1}\right)_{i,t} = \frac{P(x)}{R(x)}$, we have :
$p_t = \frac{\alpha Q(x)+\gamma R(x)}{R(x)} = \alpha\varepsilon_t + \gamma$. □

Chapter II

How recyclability affects the optimal timing of the transition [1]

Abstract The production of energy from renewable sources is much more intensive in minerals than that from fossil resources. The scarcity of certain minerals limits the potential for substituting renewable energy for scarce fossil resources. However, minerals can be recycled, while fossil resources cannot. We develop an intertemporal model to study the dynamics of the optimal energy mix in the presence of mineral intensive renewable energy and fossil energy. We analyze energy production when both mineral and fossil resources are scarce, but minerals are recyclable. We show that the greater the recycling rate of minerals, the more the energy mix should rely on renewable energy, and the sooner should investment in renewable capacity take place. We confirm these results even in the presence of other better known factors that affect the optimal schedule of resource use : growth in the productivity in the renewable sector, imperfect substitution between the two sources of energy, convex extraction costs for mineral resources and pollution from the use of fossil resources.

Contributions Mouez Fodha and Francesco Ricci drafted the two-period model. Adrien Fabre wrote and solved the model in infinite horizon, and solved various alternative specifications. Adrien Fabre coded the numerical simulations. Francesco Ricci wrote most of the paper, Adrien Fabre wrote the Appendices.

1. Joint with Mouez Fodha & Francesco Ricci, *Resource and Energy Economics*, 2020.

1 Introduction

Renewable sources of energy are generally more scattered than non-renewable ones. In particular this is the case of wind or solar energy, as compared to coal or gas. More infrastructure to capture these renewable sources, and therefore a larger quantity of mineral inputs is required to produce one unit of final energy from renewable than from non-renewable sources of energy. [2] For instance, Hertwich et al. (2015) conclude that one unit of electricity requires "11–40 times more copper for photovoltaic systems and 6–14 times more iron for wind power plants", than from conventional fossil generation, as one can see in Figure 1.1. Concern about mineral intensity of renewable sources of energy has been expressed in official reports and academic studies. [3]

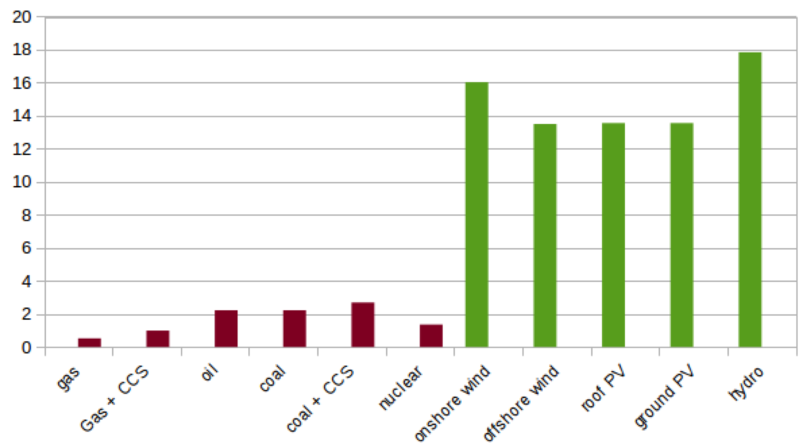


FIGURE 1.1 – Copper intensity of energy technologies, kg/MWh, from Hertwich et al. (2015)

The objective of this paper is to study how the schedule of energy production depends on mineral resources, as scarce inputs in the production of renewable energy. We present a theoretical model and bring along a novel argument in favor of early development of the production capacity for energy from renewable sources, which relies on the asymmetry between the types of natural resources used to produce energy services. When a unit of non-renewable resource is directly used as fuel to supply energy services through combustion, as in the case of oil, gas and coal, that amount of resource is definitely lost. When a unit of mineral resources is embedded in the equipment and infrastructure used to produce energy from renewable sources, it supplies a flow of energy services over an interval of time and, at the end of the life cycle of the equipment, it adds to the stock of secondary mineral resources that can be recycled. Hence, some part of the original unit of resource can provide services in the next period : the higher the recycling rate, the less one needs to extract minerals in the future. If minerals were not recyclable, they could not be reused — just as fossil resources — and the two types of resources would be analogous.

While the opportunity to recycle a non-renewable natural resource improves the production possibilities set of the economy, it also requires time as an input in order to do so. From a technological perspective, recycling first requires to use the primary (currently extracted) resource, in

2. In the case of intermittent renewable energy, backup or storage capacity requirements exacerbate this difference in mineral intensity.

3. See for instance Vidal et al. (2013), Moss et al. (2013), Ali et al. (2017), Vidal et al. (2017), as well as Arrobas et al. (2017), European Commission (2017), European Commission (2018), DOE (2013), and the U.S. Presidential executive order on the *Strategy to ensure secure and reliable supplies of critical minerals* (Dec. 2017).

order to build, with some delay, the secondary (recycled) resource. This technological constraint interacts with social preferences in determining the optimal schedule of resource extraction and use. To illustrate this, let us consider a society, with no preference for the present, where neither extraction nor recycling are costly, that wishes to maintain the level of resource use constant at a given level over a finite interval of time. If it is endowed with an abundant stock of a non-recyclable resource, it should spread it evenly over the planning horizon. If instead the resource can be partially recycled, say at a recovery rate $\delta \in (0, 1)$, with some time lag, say ten years, it should use exclusively primary resources during the first ten years, then reduce the extraction by the rate $1 - \delta$ during the following decades. As compared to the former case, the intertemporal profile of resource extraction is brought forward.

Together, the technological specificity of recycling mineral resources and the relative mineral intensity of renewable energy provide a rationale for developing more renewable energy infrastructure in the initial period than in subsequent ones and to choose a larger share for renewables in the energy mix, as compared to a case without recycling. Our analysis is based on a simplified description of the economic problem.

In our model, agents value energy services which result from a combination of energy provided by two distinct sources : the flow of renewable energy and combustion of a non-renewable fossil resource. These sources are more or less good substitutes, either because of heterogeneous uses (Chakravorty & Krulce, 1994) or because of the intermittent availability of the renewable sources (Ambec & Crampes, 2015). The production of renewable energy employs specific equipment, dubbed "green" capital, embedding mineral non-renewable resources. Part of the mineral resources embedded in the current period equipment can be also used in the next periods. The reserves of the two non-renewable resources (fossils and minerals) are scarce.The issue is the timing of their extraction that maximizes the net present value of the utility from energy services.

The answers we obtain encompass some well known arguments, as for instance that the development of renewables should be postponed in the expectations of productivity improvement of green capital. But the framework we consider allows us to put forward two original arguments : to the extent that mineral resources embedded in that equipment and infrastructure can be recycled, the development of renewable energy should be brought forward in time, and the energy mix should rely largely on renewable sources.

The assumption of a finite and scarce supply of minerals to build up the stock of green capital allows us to pinpoint these novel arguments, which rely on the intertemporal dependence in the use of the two non-renewable resources. The analysis would be affected if we were to consider competition in the use of the global supply of minerals between investment in green capital and other uses. For instance, in the extreme opposite case, one can assume that the demand for minerals from the energy sector is so small that it does not affect their equilibrium price. Minerals for investment in green capital would then be available at some exogenous marginal cost, breaking the intertemporal dependence of green capital investment decisions. [4] Let us emphasize that this is the case in most of the literature, where there is no direct intertemporal linkage of renewable energy production through scarcity of embedded non-renewable resources. The plausible case lies in between this extreme and our framework. Thus, the mechanism we point out shall be at work, though its importance should be evaluated empirically.

4. Moreover, assuming a small role of the energy sector on the market for primary mineral resources, implies that it cannot affect the market for secondary mineral resources, ruling out of the analysis any potential impact of the efficiency of the recycling technology on the timing of energy production.

Other factors can affect the optimal decision on the timing of investment in green capital. In particular, mineral extraction should be delayed when endowment in green capital is excessive.[5] In the two-period version of our model, we consider several applications and confirm that our original results hold despite the presence of alternative mechanisms. Choices related to the intertemporal allocation of scarce resources crucially depend on social preferences, specifically the willingness to smooth consumption over time. A first factor determining the timing of resource use is the expected pace of improvement in the productivity of green capital. Faster expected productivity growth tends to postpone investment in green capital, if the willingness to smooth consumption is high enough. Yet the asymmetry across resources in terms of recyclability still calls for early investment in green capital. A second factor is the degree of substitutability between the two sources of energy. Due to their physical properties or to intermittency, they are considered more or less good substitutes, or even complements, in providing energy services. We show that the higher the substitutability, the larger the marginal effects of recyclability on initial green investment and the share of renewables in the energy mix. In other words, the more flexible is the technology, the more society takes advantage of the opportunity opened by recycling. This is of special interest given that, under current technology, substitutability between conventional and renewable energy relies on storage and that electricity storage capacity is particularly intensive in minerals. A third factor we consider is the convex nature of resource extraction costs. This consideration points at the benefit of spreading resource use over time. Yet, even in the presence of convex extraction costs, an improvement in recyclability calls for earlier use of minerals, thus fostering green investment. Finally, a major rationale for early investment in green capital is based on the objective to substitute for the use of fossil energy sources, because it generates pollution. Also in this case improved recyclability fosters early green investment. Moreover, it boosts the share of renewables in the energy mix over both periods and a reduction in total polluting emissions (i.e. total fossil resource use) for sufficiently low willingness to smooth consumption.

Our work is related to several strands of the literature. The analytical approach focuses on the efficient management à la Hotelling (1931) of two types of non-renewable resources, fossil and minerals (Heal, 1993). Much attention has been paid to the case of perfect substitutes, to study the optimal order of extraction.[6] Instead, we actually consider the case of simultaneous use of the two sources of energy, conventional and renewable, in the spirit of growth theory applied to the energy transition.[7] Moreover, our results do not rely on the effect of scarcity on extraction costs and are derived in a deterministic framework.[8] Our contribution consists of an original argument concerning the optimal timing of investment in green capital, used to produce energy from renewable sources. This is related to an extensive literature covering the policies associated

5. This endowment results from investment before the start of optimal regulation. In principle it, may exceed what the optimal regulator would have chosen. In this case, the regulator would choose to rely initially only on the endowment and then, for a few initial periods, only on its recycled part, before beginning to extract minerals to add to this part. We consider this case reminiscent of investment in photovoltaic capacity in Spain, although it does not seem empirically plausible (see discussion at the end of Section 3).

6. See in particular the "least cost first" principle in Herfindahl (1967) and its qualifications (Kemp & Van Long, 1980 ; Lewis, 1982 ; Amigues et al., 1998). The case of imperfect substitution across non-renewable resources is considered in Wirl (1988) and Chakravorty & Krulce (1994). Also, the case of renewable resources has longtime been studied as a permanent shift to a perfect substitute (Tahvonen & Salo, 2001 ; Tsur & Zemel, 2005).

7. For instance Smulders & de Nooij (2003) or Grimaud & Rouge (2008) –where the labor supply is equivalent to a constant flow of renewable energy–, Pittel & Bretschger (2010), Hart (2019).

8. This differs from much of the related literature : the stochastic framework is used to analyze R&D investment to introduce an abundant substitute to the non-renewable resource (Davison, 1978 ; Kamien & Schwartz, 1978 ; Dasgupta et al., 1982), and the stock effect on extraction cost in the analysis of the optimal switching to a backstop technology (Oren & Powell, 1985 and citations therein).

with the energy transition. Among the wealth of arguments that have been put forward, some of which discussed in the previous paragraph, we recall the following. Amigues et al. (2015) point out that, in the presence of capital adjustment costs, investment to build the infrastructure for the production of renewable energy should begin early on and be spread out over time. Vogt-Schilb et al. (2018) argue that early investment in green capital is particularly valuable in the energy sector because of the long-lived nature of such capital. Lemoine & Traeger (2014) explain how uncertainty and irreversibility, due to lagged damages and investment, together affect the optimal timing of pollution abatement. [9] Technological progress resulting from learning-by-doing calls for early investment (Kverndokk & Rosendahl, 2007). As put forward in Goulder & Schneider (1999), the optimal investment in carbon free capital is affected by the fact that R&D expenditure can be targeted to such technologies. Boosting early investment may be essential to trigger sufficient R&D to escape a lock-in in the polluting technology (Acemoglu et al., 2012). This rich literature adequately examines different aspects of the timing of the energy transition, yet none of them embeds the dependency of renewable production on recyclable but scarce minerals.

In our analysis, recycling is crucial for the results. The efficient paths of resource extraction and recycling are considered as early as Weinstein & Zeckhauser (1973), Schulze (1974) or Dasgupta & Heal (1979). In economies confronted to the limited availability of resources, recycling reduces the reliance on primary resources and postpones the extraction of resources. This result is extended in various dimensions, by taking into account the material balance constraint (Pittel et al., 2010) or technological progress (Di Vita, 2001). A more recent literature considers that recycling, by linking past and current production, may generate economic cycles (De Beir et al., 2010 ; Fodha & Magris, 2015 ; Boucekkine & El Ouardighi, 2016). Finally, some articles focus on market failures associated with missing markets for waste and the resulting pollution (Hoel, 1978 ; Musu & Lines, 1995). However, none of these works considers the role of recycling in the interplay between exhaustible resources and energy production. As we show hereafter, recycling of minerals is relevant to the transition to a low carbon economy, given that "the world cannot tackle climate change without adequate supply of raw materials to manufacture clean technologies" (Ali et al., 2017).

We present our model in section 2. Section 3 presents the analysis and the results of the benchmark case, with infinite horizon and specific functional forms for the utility and the production functions. Then, we consider in section 4 further issues in a two-period version of the model. First, we check that the main results hold in this version, then we consider differences in the productivity growth across the two energy types. Second, we study the role of the degree of substitutability between energy sources in the production of energy services. Third, we introduce convex extraction costs for mineral resources. Finally, we take into account environmental damages from the use of fossil resources. To conclude we give some perspectives, in particular on the determinants of the recycling rate, from which we abstract in this paper.

9. Uncertainty and irreversibility is addressed in a microeconomic perspective in Murto & Nese (2002) and Wickart & Madlener (2007), where a firm optimally chooses the timing for investing in one of two alternative energy technologies.

2 The model

We study an economy in discrete time, where periods are denoted by $t \in \mathbb{N}_0$. [10] Let us consider a representative household, whose utility is a function of consumption of energy services q_t : [11]

$$u(q_t) \tag{2.1}$$

with $u' > 0$, $u'' \leq 0$.

Energy services combine two flows : energy from non-renewable resources, x_t, and energy from renewable sources, y_t. Formally we write :

$$q_t = Q(x_t, y_t) \tag{2.2}$$

with $Q_i' > 0$, $Q_i'' \leq 0$ $i \in \{x, y\}$. The degree to which the two types of energy can be combined to produce energy services may vary from perfect substitutability to perfect complementarity. [12]

The energy flow x_t is produced transforming the quantity of extracted non-renewable resource $f_t \geq 0$, which we dub fossil resources, according to the linear production function :

$$x_t = A_t f_t \tag{2.3}$$

where A_t is the exogenous productivity index. Resource extraction is cost-less. [13] The quantity of fossil resources is limited, it is initially available in a finite stock F and is directly reduced by extraction :

$$F \geq \sum_{t \geq 0} f_t. \tag{2.4}$$

The flow of energy y_t is produced employing a specific stock of capital K_t, which we dub "green" capital, according to the linear technology :

$$y_t = B_t K_t \tag{2.5}$$

where B_t is the exogenous productivity index. Green capital is built out of minerals. Specifically, the capital stock at date t is the sum of minerals extracted at date t —the primary resource m_t— and the stock of secondary minerals recycled from previous period's green capital δK_{t-1}. The exogenous parameter $\delta \in [0, 1]$ measures the rate at which minerals embedded in the capital stock can be recycled from one period to the next. We implicitly assume perfect substitutability between primary and recycled mineral resources, and the possibility of infinite recycling. [14] Defining

10. With a slight abuse of notation, for two dates $t_2 > t_1 \geq 0$ we write $t \in [t_1, t_2]$ to refer to $t \in [t_1, t_2] \cap \mathbb{N}_0$ or $t \in \{t_1; t_1 + 1; ...; t_2\}$. Similarly, we simply write $t \geq 0$ for $t \in \mathbb{N}_0$.

11. For the moment we abstract from any influence on the household's utility from the energy system. In section 4 we assume that utility also depends on the types of energy sources that are used to produce energy services, namely that the use of one source also generates disutility due to pollution.

12. Two approaches can be considered. Either firms sell energy services by using the two types of energy. This is the case, for instance, of a power company generating electricity out of a differentiated portfolio of power stations, some based on conventional fossil resources, others on wind and solar power. Alternatively, one can consider that households directly consume the two resources. For instance, a household endowed of a solar thermal panel and a gas fueled heater to heat water, can use the two sources of energy as imperfect substitutes due to the intermittent nature of the former. We analyze the role of this assumption in section 4.2.

13. We consider costly extraction in section 4.3.

14. In this article, we do not take into account the cost of waste recovery and processing and the lower quality of recycled resources. Di Vita (2007) takes into account imperfect substitutability between the non-renewable resource and recycled waste in the production process. He analyzes the economic growth rate and the time profile of resource

$K_{-1} \geq 0$ as the stock of minerals embedded in the capital stock before date 0, and assuming a constant recycling rate, the history of mineral extraction determines the stock of green capital : [15]

$$K_t = K_{-1}\delta^{t+1} + \sum_{\tau=0}^{t} m_\tau \delta^{t-\tau}. \tag{2.6}$$

Notice that with exogenous efficiency of the recycling technology, the parameter δ can be interpreted as the complement of the depreciation factor of capital in a standard accumulation process. An increase in the recycling rate could be equivalent to a decrease in the depreciation rate. Nevertheless, in our case, investment here consists of mineral resources, differently from the standard notion of capital. [16] Therefore, green capital is limited by a threshold determined by the total stock of resources. Minerals are non-renewable resources, initially available in a finite stock M. Primary extraction is constrained over time by [17]

$$M \geq \sum_{t \geq 0} m_t. \tag{2.7}$$

In our framework the distinction between fossil and renewable sources of energy hinges on the recycling rate of minerals δ. If minerals were perfectly recyclable, i.e. $\delta = 1$, it would be possible to produce forever a flow $B_t M$ of renewable energy, once the specific equipment had been installed at its maximum potential. If minerals were not recyclable, i.e. $\delta = 0$, they could not be used twice —just as fossil resources— and the two types of resources would be analogous.

We analyze optimal trajectories, assuming that a benevolent planner chooses the path of resource extraction that maximizes intertemporal discounted utility of the representative household, subject to technology constraints and resource dynamics. It applies a social pure discount rate $\rho > 0$ and solves the following problem

$$\begin{aligned} (\mathcal{P}): \quad & \max_{f_t, m_t} \sum_{t \geq 0} \frac{1}{(1+\rho)^t} u(q_t) \\ & \text{subject to (2.2)} - \text{(2.7) and } f_t, m_t \geq 0 \\ & \text{with } M, F, K_{-1} \text{ given.} \end{aligned}$$

extraction. Lafforgue & Rouge (2019) assume that the quality of recycled materials evolves and could make them ultimately unproductive. Like these authors and much of the literature, we also restrict our analysis to the case of an exogenous recycling rate.

15. In practice, both types of energy sources require specific capital embedding some mineral resources. Our focus is the asymmetry in mineral intensity between the specific capital for each energy source. We therefore adopt the extreme assumption that only one energy source relies on the specific capital, so as to simplify the analysis, without loosing in the qualitative features of our model.

16. In the standard approach, investment results from non consumed output. In our setting this could consist of energy services not devoted to their consumption q_t. Instead, under our assumption, the stock of green capital consists of a stock of productive mineral resources.

17. As explained in the Introduction, this is a crucial assumption for our analysis. The results concerning the role of the mineral recycling rate for initial green investment and the energy mix change drastically if, instead of (2.7), one considers a perfectly elastic supply of m_t at some exogenous marginal cost representing the relative intensity in minerals of renewable energy production as compared to conventional energy.

3 Optimal energy production with infinite horizon

In this section, we further specify the production and utility functions, in order to be able to characterize the optimal policy by closed-form solutions. Specifically, we assume a unitary elasticity of substitution between fossil and renewable energy

$$Q(x_t, y_t) = x_t^{\alpha} y_t^{1-\alpha} \tag{3.1}$$

with $\alpha \in (0,1)$. Moreover, we restrict the analysis to the case of constant and equal productivity, and set $\forall t\ A_t = B_t = 1$. We also assume a utility function with a constant elasticity of intertemporal substitution of consumption [18]

$$u(q_t) = \frac{1}{1-\varepsilon} q_t^{1-\varepsilon} \tag{3.2}$$

with $\varepsilon > 0$.

These assumptions imply that the extraction of fossil resources is always positive, i.e. $\forall t,\ f_t > 0$. In fact, if $f_t = 0$ at some t, $q_t = 0$, which is suboptimal since the marginal utility of q is infinite at $q = 0$. The reasoning applies to green capital, so that $\forall t,\ K_t > 0$. The same argument applies to the extraction of mineral resources in absence of recycling, that is $\forall t,\ m_t > 0$ if $\delta = 0$. In this special case the economy relies on the use of two non-renewable resources as imperfect substitutes for consumption. Along the optimal path, the input ratio is held constant and equal to the relative resource endowment, i.e. $t_t/k_t = f_t/m_t = F/M$. The extraction of the two non-renewable resources, as well as the production of renewable energy and consumption, decline at the common pace dictated by the factor $(1+\rho)^{-\frac{t}{\varepsilon}}$. [19]

When instead the equipment for the production of renewable energy is recyclable, i.e. if $\delta > 0$, the argument does not apply to the extraction of minerals. In fact, the production of renewable energy could be positive, i.e. $y_t > 0$, at some date t even in the absence of contemporaneous extraction of primary mineral resource, i.e. even if $m_t = 0$, to the extent that the specialized capital stock was positive in the previous period, $K_{t-1} > 0$, and it would be precisely equal to $y_t = \delta K_{t-1} > 0$.

There are two distinct potential reasons for shutting down the mine at some finite date. First of all, the opportunity to recycle minerals embedded in capital introduces an incentive to put forward the extraction date. To see this, consider the extreme case of a 100% recycling rate, i.e. $\delta = 1$. In this case, given our assumption of costless extraction, there is no gain from leaving any mineral resource underground for future use. It is clearly optimal to choose $m_0 = M$ and $m_t = 0$ for any $t \geq 1$. In our analysis we take into account the possibility that along the optimal path extraction comes to an end in finite time, and denote by $\bar{t}$ the last period during which extraction is positive. Second, there may be situations where it is preferable to initially keep mines closed and begin extracting only at some later date. This is the case when the economy is endowed of a large initial green capital stock, but only a relatively small stock of primary mineral resources. By choosing $m_t = 0$ over an initial interval $[0, \underline{t})$, one can delay the use of the limited resource stock M to periods $t \geq \underline{t}$, while keeping the renewable energy input for consumption at rate $y_t = K_{-1}\delta^{t+1}$ for $t < \underline{t}$.

We therefore search for the extraction paths of the two resources, such that $\forall t\ f_t > 0$, $\forall t \in [\underline{t}, \bar{t}]$

18. The elasticity of intertemporal substitution of consumption equals $1/\varepsilon$. For $\varepsilon = 1$, $u(q_t) = \ln q_t$.
19. This sub-case is embedded in Proposition 3.1.

$m_t > 0$ and otherwise $m_t = 0$, where periods $\underline{t}$ and $\bar{t}$ have to be chosen.[20] The planner's problem is

$$\max_{f_t, m_t} \sum_{t=0}^{\underline{t}-1} \left(\frac{1}{1+\rho}\right)^t \left(\frac{f_t^\alpha \left(\delta^{t+1} K_{-1}\right)^{1-\alpha}}{1-\varepsilon}\right)^{1-\varepsilon}$$
$$+ \sum_{t=\underline{t}}^{\bar{t}} \left(\frac{1}{1+\rho}\right)^t \left(\frac{f_t^\alpha \left(\delta^{t+1} K_{-1} + \sum_{\tau=\underline{t}}^{t} \delta^{t-\tau} m_\tau\right)^{1-\alpha}}{1-\varepsilon}\right)^{1-\varepsilon} \tag{3.3}$$
$$+ \sum_{t=\bar{t}+1}^{\infty} \left(\frac{1}{1+\rho}\right)^t \left(\frac{f_t^\alpha \left(\delta^{t+1} K_{-1} + \delta^{t-\bar{t}} \sum_{\tau=\underline{t}}^{\bar{t}} \delta^{\bar{t}-\tau} m_\tau\right)^{1-\alpha}}{1-\varepsilon}\right)^{1-\varepsilon}$$
$$+ \lambda \left(F - \sum_{t=0}^{\infty} f_t\right) + \nu \left(M - \sum_{\tau=\underline{t}}^{\bar{t}} m_\tau\right)$$

where λ, $\nu \geq 0$ are the values of the fossil and mineral resource stocks respectively.

The optimal policy is characterized by the following.

Proposition 3.1. *The unique trajectories solving problem (3.3), are of three types depending on initial capital and resource stocks, and on preference and technological parameters.*

1. *If the technological efficiency of recycling is above the* modified social discount factor r, *i.e. if* $\delta \geq r := (1+\rho)^{-\frac{1}{\varepsilon}}$, *the mineral resource is exhausted in the first period, i.e.* $\underline{t} = \bar{t} = 0$, *while the fossil resource is extracted at an exponentially declining rate*

$$f_t = F(1-R)R^t \tag{3.4}$$

   where $R := \left(\frac{\delta^{(1-\alpha)(1-\varepsilon)}}{1+\rho}\right)^{\frac{1}{1-\alpha(1-\varepsilon)}}$, *for all* $t \geq 0$.

2. *If instead* $\delta < r$, *both mineral and fossil resources are exhausted over the infinite horizon. There are two distinct types of trajectories in this case.*

   (a) *If the stock of primary mineral resources is abundant relatively to the stock of green capital available in the first period, i.e. if* $\frac{M}{\delta K_{-1}} \geq \frac{r-\delta}{1-r}$, *both fossil and mineral resources are extracted at all periods, i.e.* $\underline{t} = 0$ *and* $\bar{t} = \infty$, *and from the second period onward their extraction falls at a common exponential rate, dictated by the modified discount factor,* r. *While fossil resource extraction declines from the first to the second period according to factor* r, *the extraction of the mineral resource between the first and second*

20. In our deterministic framework, the optimal policy rules out any path with intermittent extraction of minerals. This is demonstrated in Appendix B.1, but intuitively, the Bellman principle of optimality implies that if along the optimal path extraction comes to an end at $\bar{t}$, it is not efficient to open again the mine at some later period $\tilde{t} > \bar{t}$. Suppose in fact that it is optimal to chose $m_{\tilde{t}} > 0$. It makes sense to keep $m_{\tilde{t}-1} = 0$ at $\tilde{t}-1$ only if the capital stock $K_{\tilde{t}}$ is considered too large given the remaining stocks of resources $F - \sum_{\tau=0}^{\tilde{t}-1} f_\tau$ and $M - \sum_{\tau=\underline{t}}^{\tilde{t}-1} m_\tau$. But these stocks are optimal, since they result of the extraction paths f_t and m_t up to date $\tilde{t}-1$, assumed to be optimal. Hence, $K_{\tilde{t}}$ cannot be considered excessive. This contradiction shows that our premise, according to which it is optimal to chose $m_{\tilde{t}} > 0$ when $m_{\tilde{t}-1} = 0$ is optimal, is wrong. *Mutatis mutandis* the argument holds for the interval $[0, \underline{t})$.

period follows $m_1 = (r-\delta)(m_0 + \delta K_{-1}) = (r-\delta) K_0$. *The optimal extraction path is*

$$\forall t \geq 0, \quad f_t = (1-r) F r^t \tag{3.5}$$

$$t = 0, \quad m_0 = (1-r) \frac{M}{1-\delta} \left(1 - \frac{r-\delta}{1-r} \frac{\delta K_{-1}}{M}\right) \tag{3.6}$$

$$\forall t > 0, \quad m_t = (1-r) \frac{M}{1-\delta} \left(1 + \delta \frac{K_{-1}}{M}\right) \left(1 - \frac{\delta}{r}\right) r^t \tag{3.7}$$

(b) *If instead* $\frac{M}{\delta K_{-1}} < \frac{r-\delta}{1-r}$, *extraction of the mineral resource is delayed, i.e.* $\underline{t} \geq 1$ *and* $\bar{t} = \infty$. *The optimal* $\underline{t}$ *is the lowest non-negative integer at or above the value* $\ln\left(\frac{M}{\delta K_{-1}} \frac{1-r}{r-\delta}\right) / \ln \delta$. *Over the first interval of time fossil resource extraction declines according to the factor R. From* $\underline{t}+1$ *onward, the extraction of both resources falls at the common rate r. Between period* $\underline{t}$ *and* $\underline{t}+1$ *the extraction of fossil resources declines at rate r while that of minerals follows* $m_{\underline{t}+1} = (r-\delta)\left(m_{\underline{t}} + \delta^{\underline{t}+1} K_{-1}\right)$. *In this case*

$$\forall t < \underline{t}, \quad m_t = 0 \quad ; \quad f_t = \left(\frac{1-R^{\underline{t}}}{1-R} + \Gamma(\underline{t}) \frac{r^{\underline{t}}}{1-r}\right)^{-1} F R^t \tag{3.8}$$

$$\forall t \geq \underline{t}, \quad f_t = \left(\Gamma(\underline{t}) \frac{1-R^{\underline{t}}}{1-R} + \frac{r^{\underline{t}}}{1-r}\right)^{-1} F r^t \tag{3.9}$$

$$t = \underline{t}, \quad m_{\underline{t}} = (1-r) \frac{M}{1-\delta} \left(1 - \delta^{\underline{t}} \frac{r-\delta}{1-r} \frac{\delta K_{-1}}{M}\right) \tag{3.10}$$

$$\forall t > \underline{t}, \quad m_t = \frac{1-r}{1-\delta} \left(M + \delta^{\underline{t}+1} K_{-1}\right) \left(1 - \frac{\delta}{r}\right) r^{t-\underline{t}} \tag{3.11}$$

where $\Gamma(\underline{t}) := \left(\frac{r\delta(1-\delta)K_{-1}}{(1-r)(M+\delta^{\underline{t}+1}K_{-1})}\right)^{\frac{(1-\alpha)(1-\varepsilon)}{1-\alpha(1-\varepsilon)}}$.

Démonstration. The detailed proof is in Appendix A and B.

□

Let us explain the optimal trajectories of resource extraction and energy production specified in Proposition 3.1 and comment on them.

First, notice that the Hotelling principle for the efficient management of non-renewable resources applies to our framework. When the optimal policy maintains a constant input ratio, consumption falls at the same rate as the common rate driving the decline in resource extraction. Say that q declines at a factor $g \in (0,1)$, i.e. $q_{t+1} = g q_t$. Then the value of a marginal unit of the resource mix increases at rate $p_{t+1}/p_t = g^{-\varepsilon}$. Along the optimal trajectory from period 1 onward in case (*2.a*), or from period $\underline{t}+1$ onward in trajectory (*2.b*), the optimal path of resource extraction implies $g = r$, therefore $p_{t+1}/p_t = r^{-\varepsilon} = 1+\rho$: the value of a marginal unit of resource increases at the pure discount rate, as in Hotelling (1931).[21]

Second, the asymmetry between the two types of resources, concerning the possibility to recycle them, implies a difference in their optimal extraction paths. To see this let us focus on the case of moderate recycling ($\delta < r$) and no endowment of green capital ($K_{-1} = 0$), a sub-case of (*2.a*) in Proposition 3.1. In this case, the initial ratio of resource extraction f_0/m_0 equals the initial input ratio f_0/K_0. As previously argued, without recyclability, it is optimal to choose $f_0/m_0 = F/M$,

21. p_t is the marginal value of energy services, to which the marginal values of mineral and fossil resources extracted are proportional.

according to the relative resource endowment (set $K_{-1} = \delta = 0$ in (3.6) and compare to (3.5)). When green capital can be recycled, but $K_{-1} = 0$, we see from (3.6) that the extraction and input ratios are initially biased toward more intensive use of mineral $f_0/m_0 = (1-\delta) F/M$. This first period choice is the same as the one made in an economy endowed of a larger stock of non-renewable and non-recyclable mineral resources of size $\widehat{M} := M/(1-\delta)$. The stock $\widehat{M}$ is the initial endowment adjusted for recycling and measures the maximum feasible amount of mineral inputs that can be used in the production of renewable energy over time, i.e. $\widehat{M} = \sum_{t=0}^{\infty} \delta^t M$ obtained by extracting all minerals in the first period ($\underline{t} = 0$ and $\overline{t} = 0$). This observation points to the fact that the possibility of recycling the mineral resource embedded in green capital is equivalent to an endowment of a larger stock of mineral resources. Since, due to $\delta > 0$, mineral resources are relatively more abundant, the constant input ratio f_t/K_t is optimally chosen lower. However, the ratio of resource extraction f_t/m_t can only be kept constant from period 1 onward, if mineral extraction is adjusted at date 0 to account for the absence of recycled resources at that date. In so doing, the input ratio f_t/K_t remains constant. As a consequence the ratio of resource extraction, f_t/m_t, is increased after the initial period. [22] The following statement summarizes this analysis.

Corollaire 3.1. *When $K_{-1} = 0$ and $\delta < r := (1+\rho)^{-\frac{1}{\varepsilon}}$, the solution of problem (3.3) implies that the larger is the recycling rate $\delta \in [0, r)$, the more intensive in renewable energy is the constant input ratio, the greater is the extraction of minerals in the first period and green capital at every period, the more are extracting activities concentrated on minerals initially and on fossil resources from the second period onward.*

$$\forall t \geq 0 \; \frac{x_t}{y_t} = \frac{f_t}{K_t} = \frac{F}{\widehat{M}} \quad ; \quad m_0 = (1-r)\,\widehat{M} \quad ; \quad \forall t \geq 1 \; \frac{f_t}{m_t} = \frac{r}{r-\delta} \frac{F}{\widehat{M}} \, . \tag{3.12}$$

Démonstration. The value of m_0 is an application of (3.6) in Proposition 3.1. We have $\frac{\partial m_0}{\partial \delta} = \frac{m_0}{1-\delta} > 0$, $\frac{dK_t}{d\delta} = \frac{dm_0}{d\delta} r^t > 0$ and $\frac{dm_t}{d\delta} = -\left(\frac{1-r}{1-\delta}\right)^2 M r^t < 0$. The result on the input ratio holds because, as argued in the main text f_t and K_t grow at the same rate r at any date. Applying results for the case (*2.a*) in Proposition 3.1, we get the ratio of resource extraction for $t \geq 1$. Thus $\frac{\partial f_t/m_t}{\partial \delta} = r \frac{1-r}{(r-\delta)^2} \frac{F}{M} > 0$ and $\frac{f_0}{m_0} < \frac{f_t}{m_t}$ for $t \geq 1$. □

Figure 3.1 illustrates the optimal paths of extraction of mineral and fossil resources, of green capital and consumption. [23] It represents the cases of two economies differing by the recycling rate δ under the assumption of case (*2.a*) where $r > \delta$ and no green capital endowment. According to (3.5) fossil extraction does not depend on δ. We can see that the dynamics of mineral resource extraction m is qualitatively affected (the two curves cross each other), while that of consumption q and green capital K only shift upwards in levels with the rate of recycling.

The results in Corollary 3.1 have relevant policy implications. On the one hand, the empirically grounded observation that the production of renewable energy relies on the use of specific non-renewable resources, namely minerals, suggests that the economy is poorer than it would be if the renewable energy could be produced out of non exhaustible inputs. From this point of view, the observation points to a limitation of renewable energy as a factor to overcome the limits to growth. In terms of our framework, this argument is represented by the lower value of welfare

22. $K_{-1} = 0$ implies $f_0/K_0 = f_0/m_0$. From case (*2.a*) in Proposition 3.1 $\forall t \geq 1$, $f_t/m_t = f_{t+1}/m_{t+1}$, and $f_1/m_1 = r f_0/((r-\delta) K_0)$. Hence the upward jump in the extraction ratio from period 0 to period 1 : $f_1/m_1 > f_0/m_0$.

23. Our benchmark calibration is $\rho = .04$, $\delta = .5$, $\alpha = .7$, $K_{-1} = 0$, $M = .5$, $F = 3$, $\frac{q}{f^\alpha K^{1-\alpha}} = 4$. We choose $\varepsilon = .2$ for an illustrative purpose, since most of the dynamics takes place over the very first periods in this case.

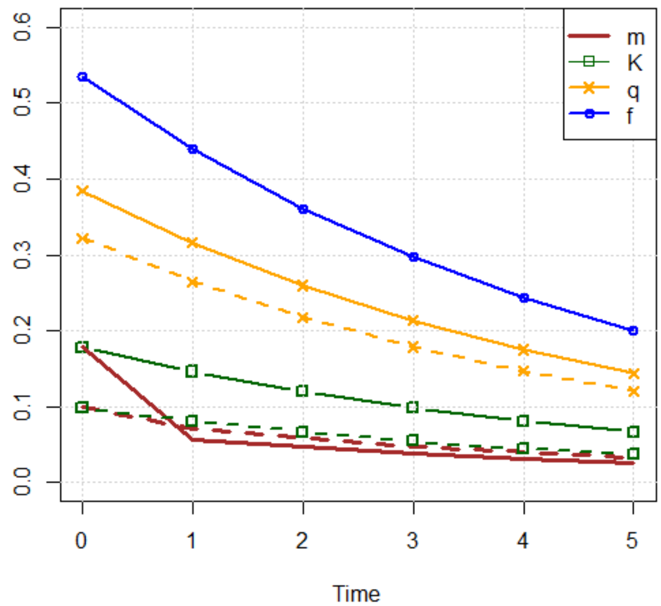


FIGURE 3.1 – Resource extraction, green capital and consumption paths for two different recycling rates : continuous lines for $\delta = 0.5$, dashed lines for $\delta = 0.1$ (see calibration footnote 23).

ceteris paribus when $\delta < 1$ than when $\delta = 1$.[24] This observation provides an argument stating that the potential production of renewable energy is more limited than generally thought. We refer to this argument as the *pessimistic stance*.

On the other hand, our analysis illustrates that the possibility to recycle minerals embedded in green capital makes it preferable to choose an energy mix composed of more renewable energy and less conventional fossil resources. Hence, adding a plausible assumption on the recycling technology to the same empirical observation, we provide a *pro renewable energy* argument, partially countering the *pessimistic stance*.

Moreover, we present an original argument in favor of a *pro active* renewable energy policy. We show that for a given amount of mineral resources to be devoted to the production of renewable energy, we should skew extraction toward the present the greater the recyclability of minerals. In other words, because minerals are recyclable and fossil resources are not, we should develop as soon as possible the green capital embedding the minerals, that allows us to produce renewable energy and to substitute for conventional fossil energy. This is found in Corollary 3.1, as well as in the extreme in case (*1.*) of Proposition 3.1 where minerals are entirely embedded in green capital from $t = 0$. Notice that this original *pro active* argument is grounded on the same empirical observation underlying the *pessimistic stance*. It relies on the flexibility in scheduling resource use typical of the management of non-renewable resources. In fact, putting forward the potential of future production of renewable energy is off the production possibility set in commonly used models with renewable and non-renewable sources of energy (e.g. Moreaux & Ricci, 2005).

Our discussion above abstracts from several potential reasons for putting forward or for postponing investment in green capital. In the next section we review a few of them. The framework in Proposition 3.1 provides already a possible reason for delaying investment. It could be that at the start of the planning horizon, the economy has inherited of a large stock of green capital. If pre-

24. In fact, welfare always increases with δ (Appendix C.6).

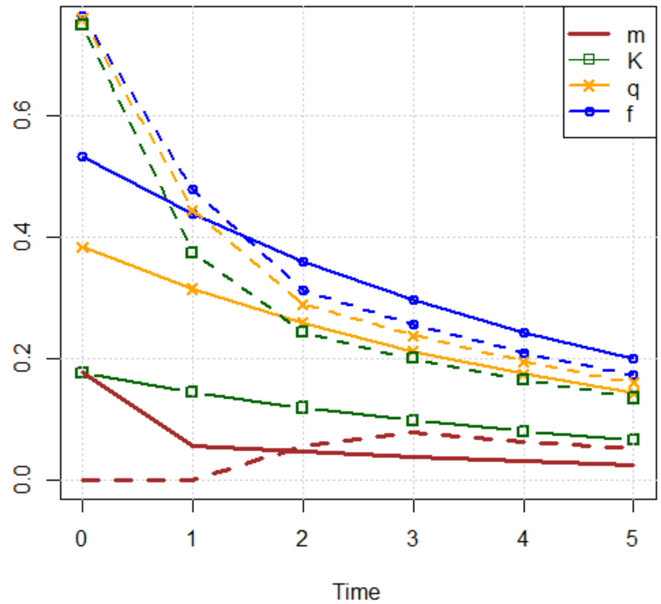


FIGURE 3.2 – Resource extraction, green capital and consumption paths for two endowments in green capital : continuous lines for $K_{-1} = 0$, dashed lines for $K_{-1} = 1.5$ (see calibration footnote 23).

vious investment decisions were not optimal, and inefficiently biased toward renewable resources, the resulting stock of green capital, and thus of secondary mineral resource available in the first period, could exceed the desirable initial stock of capital for the first period. This corresponds to case $(2.b)$ in Proposition 3.1. Figure 3.2 shows how the optimal paths of four endogenous variables –extraction of fossil and mineral resources, green capital, and consumption– vary with the endowment of green capital. The level of this endowment is chosen to represent the qualitative features of cases $(2.a)$ and $(2.b)$ in Proposition 3.1. In the latter case it is optimal to delay the extraction of mineral resources (as $\underline{t} > 0$). Nevertheless, in this case, production of renewable energy is initially quite high, and actually higher than socially desirable. In practice, this case may be of little relevance.

Two further remarks on case $(2.b)$ are worthwhile. First, over the interval of time $[0, \underline{t})$ the stock of green capital declines at rate δ instead of the socially desired rate $r > \delta$. Though abundant, green capital is still valuable because productive, and it is therefore used at full capacity. As a result though, over this interval of time, the rate at which fossil extraction decreases is adjusted and differs from the one prevailing in presence of mineral extraction.[25] A similar adjustment to the extraction of fossil resources applies in case $(1.)$ of a sufficiently efficient recycling technology. Second, the marginal effect of an increase in the recycling rate δ is more complex in the case $(2.b)$ of Proposition 3.1 than in the case $(2.a)$ treated in Proposition 3.1. On the one hand the same forces presented in Corollary 3.1 apply. Yet now, a countervailing effect operates through the fact that more secondary mineral resources are made available by the increase in δ over the initial interval $[0, \underline{t})$. The beginning of extraction may be delayed, and the initial extraction of mineral

25. More precisely, we deduce from Appendix C.1 that the optimal rate of decay for fossil extraction is the closest one between r and R from the pure discount factor $\frac{1}{1+\rho}$.

resources may decline with δ.[26] That being said, in general, the higher the recycling rate, the higher the optimal initial extraction of minerals, and the lesser the subsequent ones, unless reserves M are very low as compared to endowment in green capital. Indeed, the higher the recycling rate, the more abundant are resources in the future. This weakens the trade-off between present and future consumption, allowing for earlier extraction. However, absent sufficient reserves for the future, another effect dominates : the higher the recycling rate, the more one benefits from past investment in green capital, and the less one needs to extract minerals in the future. In practice, we argue that recoverable resources M is one order of magnitude larger than green capital K_{-1} for base metals (Singer, 2017), so we can reasonably assume that the realistic case is the case (*2.a*),[27] with $K_{-1} \approx 0$ and $\underline{t} = 0$.

4 Extensions in a two-period model

In the previous section, we analyzed how the asymmetry in recyclability between inputs used in the production of conventional vs. renewable energy affects the optimal timing of energy production. In this section, we consider other factors affecting this timing, and in particular initial investment in green capital m_0 and the energy mix. In order to develop these extensions in a clear and tractable way, we consider the two-period version of the model presented in section 2, with $t \in \{0; 1\}$. We check the validity of the following results in a number of extensions. First, the existence of a threshold on recyclability of minerals such that primary mineral resources are exhausted in the first period, for δ above the threshold, as established in Proposition 3.1. Second, the fact that, for δ below this threshold, a marginal increase in recyclability fosters first period mineral resources use and investment in green capital (i.e. $\partial m_0/\partial\delta, \partial K_0/\partial\delta > 0$), and makes the input ratio more intensive in renewable energy ($\partial(f_0/K_0)/\partial\delta < 0$), as established in Corollary 3.1.[28]

To begin with, we show how the results adjust to the finite horizon case, studying the benchmark case with constant relative risk aversion (CRRA) utility function. We disentangle two mechanisms by first studying the sub-case of a logarithmic utility, then discuss the role of the preference for intertemporal consumption smoothing in the optimal timing of energy production. Within this simplified framework, we study how expected technological progress, such as improved productivity of minerals in renewable energy equipment, affects the optimal investment in green capital. We move on to consider alternative assumptions on the production technology concerning the degree of substitutability between energy services provided by the two types of resources within each period.[29] Next, we consider the role played by convex extraction costs in determining the optimal time of investment in green capital. Finally, we allow for environmental damages from the use of

26. We have $\frac{dm_{\underline{t}}}{d\delta} > 0 \iff \forall t > \underline{t},\ \frac{dm_t}{d\delta} < 0 \iff M > \delta^{\underline{t}} K_{-1} \left(\frac{(r-\delta)(1-\delta)}{1-r} (\underline{t}+1) - \delta \right)$ and $\frac{d\underline{t}}{d\delta} = \frac{1}{(r-\delta)\ln(\delta)} - \ln\left(\frac{M}{K_{-1}} \frac{1-r}{r-\delta} \right) / \delta \ln^2(\delta)$. One can check that, even in the range of parameters of case (*2.b*) ($\delta < r$ and $\frac{M}{\delta K_{-1}} < \frac{r-\delta}{1-r}$) both signs are possible for each of these derivatives.

27. Indeed, $\delta \geq r$ does not seem realistic. An upper credible value for the pure discount rate ρ is 0.05, while the inverse of the elasticity of intertemporal substitution ε can reasonably be assumed higher than 0.5. Combining these conservative figures gives a low estimate for r : 0.9. Taking more common values for ρ and ε would yield an even higher threshold r, so that for any realistic value of the recycling rate δ, it is extremely likely to have $\delta < r$ and to be in the case where the optimal path is an endless extraction.

28. These are the main original and policy relevant results of our analysis. In the versions of model presented in this section, second period outcomes are affected by the fact that it is the last period in a finite horizon with non-renewable resources. Hence the results we obtain for second period outcomes are less interesting and robust, that those for m_0 and f_0/K_0 on which we focus.

29. Alternatively, this can be interpreted as a feature related to preferences.

fossil resources, which also affect the optimal path of resource use.

4.1 The benchmark model with technological change

Let us consider first the case with CRRA utility function, Cobb-Douglas production function and non constant productivities of resource inputs. In a two-period setting the planner's problem is as follows :

$$\begin{aligned} &\max \frac{q_0^{1-\varepsilon}}{1-\varepsilon} + \frac{1}{1+\rho}\frac{q_1^{1-\varepsilon}}{1-\varepsilon} \\ &q_t = (A_t f_t)^{\alpha} (B_t K_t)^{1-\alpha} \ , t \in \{0;1\} \\ &K_0 = m_0 \ , K_1 = m_1 + \delta m_0 \\ &f_0 + f_1 \leq F \\ &m_0 + m_1 \leq M \end{aligned} \tag{4.1}$$

with m_0, m_1, f_0, and $f_1 \geq 0$, where $\alpha \in (0,1)$ and $\varepsilon > 0$ (log utility for $\varepsilon = 1$).

Proposition 4.1. *The unique trajectories solving problem (4.1) are of two types. If $\delta < \widetilde{\delta} \equiv \frac{\widetilde{r}}{1+\widetilde{r}}$ where*

$$\widetilde{r} := \frac{1}{1+\rho}\left(\frac{q_1}{q_0}\right)^{1-\varepsilon}, \tag{4.2}$$

it is optimal to extract the mineral resource in both periods, as follows

$$m_0 = \frac{\frac{1}{1-\delta}}{1+\widetilde{r}}M \ ; \ m_1 = \frac{\widetilde{r} - \frac{\delta}{1-\delta}}{1+\widetilde{r}}M \ ; \ f_0 = \frac{1}{1+\widetilde{r}}F \ ; \ f_1 = \frac{\widetilde{r}}{1+\widetilde{r}}F, \tag{4.3}$$

implying

$$\frac{q_1}{q_0} = \left[\left(\frac{A_1}{A_0}\right)^{\alpha}\left(\frac{B_1}{B_0}\right)^{1-\alpha}\right]^{\frac{1}{\varepsilon}} (1+\rho)^{-\frac{1}{\varepsilon}} (1-\delta)^{\frac{1-\alpha}{\varepsilon}} \tag{4.4}$$

Moreover $\frac{f_0}{K_0} = \frac{F}{\widehat{M}}$, $\frac{f_1}{K_1} = \frac{F}{M}$ and $\frac{K_1}{K_0} = \widetilde{r}(1-\delta)$. Therefore $\frac{\partial m_0}{\partial \delta} > 0$, $\frac{\partial f_0/K_0}{\partial \delta} < 0$, $\frac{\partial f_1/K_1}{\partial \delta} = 0$, $\frac{d(q_1/q_0)}{d\delta} < 0$ and $\frac{\partial K_1/K_0}{\partial \delta} < 0$.

If $\delta \geq \widetilde{\delta}$, where $\tilde{\delta}$ is defined using (4.2) and (4.4), the mineral resource is exhausted at date 0. The optimal resource use is $m_0 = M$, $m_1 = 0$, $f_0 = \frac{1}{1+\zeta}F$, and $f_1 = \frac{\zeta}{1+\zeta}F$, where $\zeta := \left(\left(\frac{A_1}{A_0}\right)^{\alpha}\left(\frac{B_1}{B_0}\right)^{1-\alpha}\frac{1}{1+\rho}\delta^{(1-\alpha)(1-\varepsilon)}\right)^{\frac{1}{1-\alpha(1-\varepsilon)}}$. In this case $\frac{q_1}{q_0} = \left(\left(\frac{A_1}{A_0}\right)^{\alpha}\left(\frac{B_1}{B_0}\right)^{1-\alpha}\frac{1}{1+\rho}\right)^{\frac{-\alpha}{1-\alpha(1-\varepsilon)}}\delta^{\frac{1-\alpha}{1-\alpha(1-\varepsilon)}}$ instead of (4.4). Hence $\frac{d(q_1/q_0)}{d\delta} > 0$, while $\frac{df_0}{d\delta} < 0$, $\frac{df_1}{d\delta} > 0$ if $\varepsilon < 1$ but $\frac{df_0}{d\delta} > 0$, $\frac{df_1}{d\delta} < 0$ if $\varepsilon > 1$.

Démonstration. See Appendix C.2. □

From (4.2) and (4.4), $\tilde{r}$ is the ratio of the present value current utility from energy consumption when $\delta < \widetilde{\delta}$. Hereafter, we refer to this ratio as the *gross* social discount factor. Let us begin by considering the sub-case without technological progress ($A_1/A_0 = B_1/B_0 = 1$). Moreover, first consider the case of logarithmic utility ($\varepsilon = 1$). In this case, the threshold value of the recycling rate,

$\tilde{\delta} = \frac{1}{2+\rho}$, is independent of the recycling rate and relative resource abundance, since $\tilde{r}$ is equal to the pure discount factor $\frac{1}{1+\rho}$ (see (4.2)). When $\delta > \tilde{\delta}$, all mineral resources are extracted and used in the first period, i.e. $m_0 = M$, and the decline in energy consumption is given by $\frac{q_1}{q_0} = \left(\frac{1}{1+\rho}\right)^{\alpha} \delta^{1-\alpha}$ and increases with δ. Otherwise, for δ below the threshold, minerals are extracted in both periods and consumption of energy services declines at $\frac{q_1}{q_0} = \frac{1}{1+\rho}(1-\delta)^{1-\alpha}$, a decreasing function of δ. In this case, the higher the rate of recycling, the earlier the use of primary mineral resources, the larger the initial investment in green capital, and the more intensive in renewable energy is the input ratio in the first period. These three results confirm those in Proposition 3.1 and Corollary 3.1.

Other results differ from the case with infinite horizon. First, the input ratio in the second period does not change with the rate of recycling. This difference is not surprising, since there is no advantage from recycling mineral resources used in the second period in a setting where there is no future period to use recycled resources (i.e. no third period). Second, as noticed, when $\delta < \tilde{\delta}$, energy consumption declines at a faster pace the greater is the recycling rate, while this rate of decline is unaffected by δ in the infinite horizon case. Improved δ tends to increase q_1/q_0 for unchanged intertemporal resource allocation. Yet, it also makes it more interesting to extract minerals in the first period, reducing q_1/q_0. This second substitution effect dominates the former when $\delta < \tilde{\delta}$. Finally, a higher δ affects q_1/q_0 through the positive income effect that calls for an intertemporal reallocation of mineral and fossil resources, according to social preferences on consumption smoothing, to which we turn our attention below. Notice that in this case with logarithmic utility and Cobb-Douglas production functions, the opportunity to recycle mineral resources does not affect the use of fossil resources.

As a second step, consider the case $\varepsilon \neq 1$ to study the role of preferences with respect to intertemporal consumption smoothing, in determining the timing of resource use and investment in green capital. We find that, when $\delta < \tilde{\delta}$, the decline in energy consumption (4.4) is a decreasing function of δ, more so the smaller is ε, i.e. the greater the elasticity of intertemporal substitution, $1/\varepsilon$. An improvement in the recyclability of minerals brings forward mineral resource use more so the least adverse to variability in the consumption over time is the representative household, and as a consequence the larger is the downward adjustment in optimal consumption. Since $\tilde{r} = (1+\rho)^{-\frac{1}{\varepsilon}}(1-\delta)^{\frac{1-\varepsilon}{\varepsilon}(1-\alpha)}$ (from (4.2) and (4.4)), the gross discount rate is affected by ε through two channels. First, the pure preference for the present, ρ, which directly affects the gross discount factor and therefore the timing of consumption and thus of resource use. Second, the gross discount factor is affected by the prospective decline in consumption, given by (4.4), itself influenced by the recycling technology for green capital. The expected decline in consumption tends to decrease the gross discount factor if ε is smaller than unity, i.e. for high elasticity of intertemporal substitution of consumption $1/\varepsilon$, and vice versa. As a result, the resource use tends to be brought forward, thus f_1/f_0 and m_1/m_0 to decrease. It is worthwhile noticing the asymmetry between the two resources. Inspecting (4.3) we see that a marginal increase in δ exerts two effects on m_0, a direct one and an indirect one through $\tilde{r}$. As established in Proposition 4.1, the former force dominates, so that an increase in δ reduces the ratio m_1/m_0, bringing forward mineral resource use and boosting investment in green capital during the first period, whatever ε. Nevertheless, the impact is smaller the larger is the willingness to smooth consumption over time if $\varepsilon > 1$, and vice versa, because of the above mentioned increase in the gross discount factor. In the case of fossil resources instead, only this indirect effect running through the gross discount factor is at work, so that the optimal fossil resource use is delayed (f_1/f_0 increases) if $\varepsilon > 1$ but it is brought forward (declines) if

$\varepsilon < 1$. If we interpret the objective of the planner as a welfare function across two generations, the parameter ε determines inequality aversion. While an increase in δ implies a sharper decrease of consumption across generations, the size of this change is milder the higher inequality aversion.

Our analysis shows that preferences with respect to intertemporal substitution in consumption possibilities play an important role in determining the optimal timing of resource use and investment in green capital. However, the original mechanism underscored in this paper, based on the asymmetry between the two types of resources, is still crucially at work in determining the optimal timing of investment in green capital, making it preferable to bring forward investment as the efficiency of the recycling technology increases.

Finally, consider the effect of expected technological change. The asymmetry on the optimal timing of resource use implied by the possibility to recycle minerals embedded in green capital is unaffected, since the results concerning the role of parameter δ hold independently of B_1/B_0. Nevertheless, in the case of an interior solution ($\delta < \tilde{\delta}$) prospects of technological progress do affect the optimal timing in resource use and investment in green capital, through their influence on the optimal rate of growth of energy consumption (4.4). Expected improvements in the productivity of green capital, i.e. $B_1 > B_0$, lead to higher consumption growth $\partial\left(q_1/q_0\right)/\partial B_1 > 0$. This, in turn, exerts wider effects, according to the attitude toward consumption smoothing. If $\varepsilon < 1$, slower decline in energy consumption increases the gross social discount factor $\partial\widetilde{r}/\partial B_1 > 0$, and therefore delays the extraction of mineral $\partial m_0/\partial B_1 < 0$ and fossil $\partial f_0/\partial B_1 < 0$ resources, while raising the threshold value on recyclability of minerals $\partial\widetilde{\delta}/\partial B_1 > 0$. The opposite consequences apply if $\varepsilon > 1$.

In the analysis hereafter we abstract again from technological change and assume again $\forall t$ $A_t = B_t = 1$.

4.2 Substitutability between energy services from different sources

Until now, we have assumed the specific Cobb-Douglas form (3.1) for the production function of energy services (2.2) combining services from fossil and renewable energy. This assumption simplifies the analysis, but there is no reason to believe that these two types of energy services are substitutes among each other with a constant and unitary elasticity of substitution. Thinking of electricity as an homogeneous good, one might consider that the elasticity of substitution is much larger than unity. Alternatively, one might view renewable and conventional sources of energy as quite imperfect substitutes in providing energy services, due to the intermittent availability of some renewable sources of electricity, or to physical properties (weight, density, caloric power) of some fossil sources of energy, making them drastically more efficient in some uses other than electricity production (e.g. air transportation).

The degree of substitutability between the two types of energy services may affect the optimal timing of investment in green capital. To see why, consider the heuristic extreme case without recycling, nor discounting, and completely inelastic preferences over the intertemporal consumption path of energy services ($\varepsilon = \infty$). The objective is maximized by keeping constant at $q_t = Q\left(\frac{1}{2}F, \frac{1}{2}M\right)$, whatever the elasticity of substitution between the arguments in function $Q\left(.\right)$. If this elasticity is nil, it is optimal to use half of each resource per period. If the elasticity of substitution is very large, then there is a continuum of combinations of fossil and minerals (green capital) that maximize welfare, and therefore some minerals can be used in the first period to build up more green capital, $m_0 > \frac{1}{2}M$ (though leaving welfare unaffected). Introducing recycling of green capital into the picture, the latter feature changes : welfare may be increased by bringing forward investment in green capital. In doing so, the secondary resource stock of minerals increases, so that renewable energy services in the second period decrease by less than their increment in the first period. This potentially beneficial role of recycling is less valuable in the case of moderate possibilities for substituting between the two types of energy services. In the limit, if the latter are perfect complements, bringing forward mineral extraction does not create additional value and the optimal resource use is unaffected by δ. This discussion suggests that the elasticity of substitution between the two types of energy services interacts with the preference parameters, namely the elasticity of intertemporal substitution of energy consumption, in determining the optimal timing of investment in green capital.

Modifying the planner's problem (4.1), by substituting $q_t = \left(\alpha f_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) K_t^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$ for $q_t = (A_t f_t)^{\alpha} (B_t K_t)^{1-\alpha}$ with $\sigma > 0$, we find that the interior solution (i.e. $m_1 > 0$) holds if the recycling rate is below a threshold, i.e. if $\delta < \frac{\widetilde{r}}{(1-\delta)^{1-\sigma}+\widetilde{r}}$, where we extend the definition of $\tilde{r}$ as follows

$$\widetilde{r} := \left(\frac{1}{1+\rho}\right)^{\sigma} \left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma} \tag{4.5}$$

In this case, efficient resource extraction is defined by (4.3) but for the following [30]

$$m_0 = \frac{1}{1+\widetilde{r}\,(1-\delta)^{-(1-\sigma)}}\widehat{M} \quad , \quad m_1 = \frac{\widetilde{r}\,(1-\delta)^{\sigma}-\delta}{1+\widetilde{r}\,(1-\delta)^{-(1-\sigma)}}\widehat{M} \tag{4.6}$$

and the intertemporal energy consumption ratio $\frac{q_1}{q_0}$ is implicitly defined as the solution of

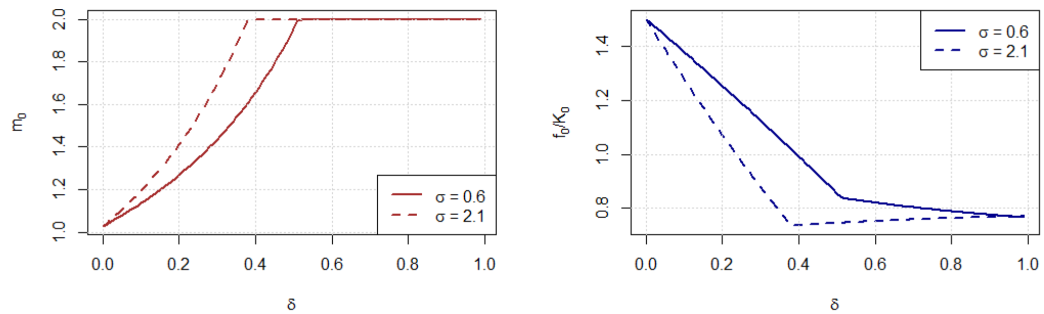
$$G\left(\frac{q_1}{q_0}, \delta\right) - \left(\frac{q_1}{q_0}\right)^{\varepsilon\sigma} (1+\rho)^{\sigma} = 0 \tag{4.7}$$

where

$$G\left(\frac{q_1}{q_0}, \delta\right) \equiv \left(\frac{\alpha F^{\frac{\sigma-1}{\sigma}} + (1-\delta)^{\sigma-1}(1-\alpha)\, M^{\frac{\sigma-1}{\sigma}} \left(\frac{1+\left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma}(1+\rho)^{-\sigma}}{1-\delta+\left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma}(1+\rho)^{-\sigma}(1-\delta)^{\sigma}}\right)^{\frac{\sigma-1}{\sigma}}}{\alpha F^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\, M^{\frac{\sigma-1}{\sigma}} \left(\frac{1+\left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma}(1+\rho)^{-\sigma}}{1-\delta+\left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma}(1+\rho)^{-\sigma}(1-\delta)^{\sigma}}\right)^{\frac{\sigma-1}{\sigma}}}\right)^{\frac{\sigma}{\sigma-1}}$$

As shown in Figure 4.1, the numerical solutions confirm that $\frac{\partial m_0}{\partial \delta} > 0$ and $\delta < \widetilde{\delta} \implies \frac{\partial f_0/K_0}{\partial \delta} < 0$, hence that our argument applies also in this case. [31] The solution changes with σ : the marginal impact of δ on the initial investment in green capital and energy mix is stronger as the elasticity of substitution between energy services increases. Moreover, this dependency is positively related to the elasticity of intertemporal substitution, $1/\varepsilon$. These findings confirm the heuristic argument developed in the previous paragraph : the flexibility in combining the two types of energy services affects the optimal timing of green investment and the optimal energy mix when green capital can be recycled. Specifically the more flexible are the preferences and the technology, the more society takes advantage of the opportunity opened by recycling. Yet, our original argument favorable to early investment and to the intensity in renewables of the energy mix apply in this more involved

30. See Appendix C.3 for the derivation of the results presented in this sub-section.
31. The sensitivity analysis confirms that these results are robust. In particular, they hold for all combinations of $\sigma \in [0.1, 10.1]$ and $\varepsilon \in [0.1, 6.1]$.



(a) Initial investment in green capital (b) First period energy mix

FIGURE 4.1 – How the solution varies with the efficiency of the recycling technology in the case of a CES production function for energy services (see calibration footnote 23).

setting. To the extent that much of the relative mineral intensity of renewables is linked to the electricity-storage technology and the aim of the latter is precisely to improve the substitutability between conventional and renewable sources of electricity, our argument is somewhat reinforced by the analysis, though of course it assumes both parameters as exogenous.

4.3 Convex extraction costs

So far, in our analysis we ruled out extraction costs. If the marginal costs of producing fossil and mineral resources increase with the extraction rate, the optimal timing of resource use, thus of investment in green capital, should be affected. In order to show this in a clear-cut way, we present a variant of our two-period model where fossil resources play no role. [32] We focus on the optimal solution with full exhaustion of the minerals stock and $m_1 > 0$, [33] and consider the following planner's problem :

$$\max \frac{1}{1-\varepsilon} m_0^{1-\varepsilon} + \frac{1}{1+\rho}\frac{1}{1-\varepsilon}\left(M-(1-\delta)\, m_0\right)^{1-\varepsilon} - \frac{c}{1+\gamma} m_0^{1+\gamma} - \frac{1}{1+\rho}\frac{c}{1+\gamma}\left(M-m_0\right)^{1+\gamma}$$

where c, $\gamma > 0$ are the extraction cost parameters, and minerals are exhausted $m_1 = M - m_0$. The first order condition is

$$P\left(m_0\right) := m_0^{-\varepsilon} - \frac{1-\delta}{1+\rho}\left(M-(1-\delta)\, m_0\right)^{-\varepsilon} = c\left(m_0^{\gamma} - \frac{1}{1+\rho}\left(M-m_0\right)^{\gamma}\right) =: C\left(m_0\right) \qquad (4.8)$$

$P\left(m_0\right)$ measures the present value of the marginal utility generated by first period mineral extraction. It is a monotonically decreasing function of m_0, taking values $+\infty$ for $m_0 = 0$, and $M^{-\varepsilon}\left(1-\frac{(1-\delta)}{1+\rho}\delta^{-\varepsilon}\right)$ for $m_0 = M$. It becomes nil at $m_0^u := \left(1-\delta+\left(\frac{1-\delta}{1+\rho}\right)^{\frac{1}{\varepsilon}}\right)^{-1} M$. $C\left(m_0\right)$ measures the present value of the marginal cost of extraction at date 0. It is an increasing function of m_0, from $-c\frac{1}{1+\rho}M^{\gamma}$ for $m_0 = 0$ up to cM^{γ} for $m_0 = M$. It becomes nil at

32. In practice we assume $\alpha = 0$ to simplify the analysis and the notations. Numerical solutions suggest that the qualitative results extend to the case of an optimized use of finite fossil resources : this has been verified for the benchmark calibration (see footnote 23), with $c = 1$, $\gamma = 2$, and ε varying from 0.1 to 3.1.

33. In the case of extraction costs for minerals, it is not necessarily the case that the stock M is optimally exhausted. This is the case only for costs sufficiently low. Extraction costs are in turn partially endogenous. Here we focus the analysis on the first order condition.

$m_0^c := \left(\frac{1}{1+\rho}\right)^{\frac{1}{\gamma}} \left(1 + \left(\frac{1}{1+\rho}\right)^{\frac{1}{\gamma}}\right)^{-1} M$. Therefore, if the two schedules cross in the space (m_0, value) for $m_0 \in [0, M]$, they do so only once. We conclude that, if $\left(1 - \frac{1-\delta}{1+\rho}\delta^{-\varepsilon}\right) < cM^{\gamma+\varepsilon}$, there exists a unique value of m_0 satisfying (4.8).

How does the presence of convex extraction costs directly affect the timing of mineral resource use ? Does it affect the role played by the efficiency of the recycling technology of minerals embedded in green capital on the timing of investment in green capital ?

To answer the former question, consider the present value of the marginal extraction cost of m_0. Notice first that when $\gamma > 0$ and in the absence of discounting $\rho = 0$, this cost is minimized by smoothing completely resource extraction $m_0 = m_1 = \frac{1}{2}M$. Under discounting, instead, this intertemporal smoothing is partial and $C(m_0)$ is minimized by partially shifting resource use to the future, i.e. $m_0 = m_0^c < m_1 = M - m_0^c$ since $\rho > 0$. These two features provide the rationale for smoothing over time and partially delaying resource extraction when the marginal extraction cost is an increasing function of the extraction rate. Notice that these considerations intervene in our problem on the right-hand-side of (4.8), and are not directly affected by the possibility to recycle minerals, on which hinges the original mechanism put forward in this article. This remark provides the answer to the second question above : a marginal improvement in δ increases the present value of the marginal utility generated by first period mineral extraction and leads to an increase in optimal m_0, and investment in green capital, for any given schedule $C(m_0)$. [34]

We have shown that, although convex extraction costs introduce an economic incentive to smooth and actually postpone extraction of minerals, and therefore the build-up of the green capital stock, our original mechanism due to the possibility of recycling minerals embedded in green capital, is still at work, since it introduces a specific incentive to bring forward *ceteris paribus* minerals extraction and investment in green capital.

4.4 Environmental damages from using fossil resources

One of the main reasons underpinning the development of renewable energy production capacity around the world is the general recognition of the social costs resulting of the energy production from fossil resources. Since Smith (1972), the literature analyzing the interplay between recycling and pollution has focused on the potential limitation of local pollution from solid waste. Our original framework allows us to introduce an indirect link between the development of recycling and the reduction of greenhouse gas emissions, to mitigate climate change, a global pollution problem. [35] Recycling influences the time profile of the energy mix. In the case of climate change related damages, the cumulative process of pollution raises the social payoff of early action. To take into account this additional factor affecting the optimal timing of investment in green capital, we extend our two-period model by assuming that using fossil resources also reduces utility. Specifically, we modify the utility function by adding a separable disutility term, convex in the current flow of pollution from the use of fossil resources : $d_t \frac{1}{\theta} f_t^{\theta}$, with $\theta > 1$ and $t \in \{0; 1\}$. In order to capture two features of the climate change problem, we consider the case where it is not socially desirable

34. Formally, one can compute from (4.8) that $\frac{dm_0}{d\delta} = -\left(\frac{\partial P(m_0)}{\partial \delta} - \frac{\partial C(m_0)}{\partial \delta}\right) / \left(\frac{\partial P(m_0)}{\partial m_0} - \frac{\partial C(m_0)}{\partial m_0}\right) > 0$, since, according to the previous analysis, the denominator is negative while $\frac{\partial C(m_0)}{\partial \delta} = 0$ and $\frac{\partial P(m_0)}{\partial \delta} = \frac{1}{1+\rho}(M - (1-\delta)m_0)^{-\varepsilon}\left(1 + \varepsilon \frac{(1-\delta)m_0}{M-(1-\delta)m_0}\right) > 0$.

35. Though the use of fossil resources is a major cause of local pollution problems too, the crucial constraint on the supply of minerals for green capital (2.7) is potentially relevant on a global scale.

to exhaust fossil resources, i.e. $f_0 + f_1 < F$, then consider that damages from first period emissions are relatively large, i.e. $d_0/d_1 > 1$ and study the impact of an increase in d_0.[36]

The planner's program is modified, and writes

$$\max \frac{1}{1-\varepsilon}\left(f_0^{\alpha} m_0^{1-\alpha}\right)^{1-\varepsilon} - d_0\frac{1}{\theta}f_0^{\theta} + \frac{1}{1+\rho}\left(\frac{1}{1-\varepsilon}\left(f_1^{\alpha}\left(m_1+\delta m_0\right)^{1-\alpha}\right)^{1-\alpha} - d_1\frac{1}{\theta}f_1^{\theta}\right) + \nu\left(M - m_0 - m_1\right)$$

We show in Appendix C.4 that the interior solution (i.e. $m_1 > 0$) holds if $\delta < \widetilde{\delta} \equiv \frac{\widetilde{r}}{1+\widetilde{r}}$ and is defined by (4.2), (4.3) but for the following

$$f_0 = \left[\frac{\alpha}{d_0}\left(\frac{\frac{1}{1-\delta}}{1+\widetilde{r}}M\right)^{(1-\alpha)(1-\varepsilon)}\right]^{\frac{1}{\theta-\alpha(1-\varepsilon)}}, \quad f_1 = \left[\frac{\alpha}{d_1}\left(\frac{\widetilde{r}}{1+\widetilde{r}}M\right)^{(1-\alpha)(1-\varepsilon)}\right]^{\frac{1}{\theta-\alpha(1-\varepsilon)}} \tag{4.9}$$

and the decline in energy consumption that is now given by

$$\frac{q_1}{q_0} = \left[\left(\frac{d_0}{d_1}\right)^{\alpha}\left(\frac{1-\delta}{1+\rho}\right)^{\theta(1-\alpha)}\right]^{\frac{1}{\theta-(1-\varepsilon)[\alpha+\theta(1-\alpha)]}}. \tag{4.10}$$

Since $\alpha \in (0,1)$, $\varepsilon > 0$, $\theta > 1$ imply $\theta - (1-\varepsilon)\left[\alpha + \theta\left(1-\alpha\right)\right] > 0$, the energy consumption declines at a faster pace with the efficiency of recycling ($\partial\frac{q_1}{q_0}/\partial\delta < 0$), and a slower rate with the importance of damages from initial polluting emissions ($\partial\frac{q_1}{q_0}/\partial d_0 > 0$). As a consequence the gross discount rate $\tilde{r}$ falls with δ and increases with d_0 if $\varepsilon < 1$, and vice versa. We find that our original mechanism is also operative in this framework. Similarly to the result in Proposition 4.1, the initial extraction rate of minerals and green investment increase with the recyclability, as well as the share of renewables in the energy mix in the first period (see Appendix C.4). In this case the energy mix is affected by δ also in the second period. In fact, improved recyclability of minerals embedded in green capital exerts the same effects discussed in detail in Section 4.1 in terms of the intertemporal allocation of fossil and mineral resources. However, in the present case the countervailing force due to the limited supply of fossil resources and their exhaustion is not active, since the total quantity of fossil resources used can vary. From (4.3) and (4.9) one can see that the use of fossil resources in the initial period moves with the recyclability in the same direction as renewables if the elasticity of the intertemporal substitution in consumption is larger than unity (i.e. $\varepsilon < 1$), and vice versa, while fossil resource use in the second period always falls with δ. Hence, improved recyclability of minerals allows society to reduce the total amount of fossil resources used when $\varepsilon > 1$, and thus increase the share of renewables in the energy mix in both periods.[37]

How is investment in green capital affected by an increase in the damage of fossil resources use in the first period, i.e. d_0? This may represent a worsening of the climate change problem, as a short-cut for the cumulative nature of damages in such a pollution control problem. We find

36. Alternative setups to study the problem could be considered. One may impose a constraining ceiling $\overline{F} < F$, such that $f_0 + f_1 \leq \overline{F}$, in the spirit of the literature on "carbon budgets" (Chakravorty et al., 2006). Moreover, the cumulative nature of the pollution problem can be explicitly considered, by assuming that the second period disutility from pollution depends on past and present use of fossil resources. Numerical solutions of the case with cumulative pollution suggest that the qualitative results hold : this has been verified for the benchmark calibration (see footnote 23), with $d = 1$, $\theta = 2$, and ε varying from 0.1 to 3.1.

37. This result would not hold if one were to adopt a "carbon budget" approach.

that an increase in d_0 does not necessarily put forward investment in green capital. In fact, for larger damage from fossils in the first period, the intuitive effect is that less fossil is used in the first period. As a consequence, the marginal utility of consumption in the first period is increased, making m_0 more valuable. This first effect calls for increasing m_0. However, a second effect, related to complementarity in production, comes from the fact that the marginal productivity of one resource increases with the use of the other resource. This calls for shifting the use of minerals to the second period, in order to postpone the use of the fossil resource. The balance between these two effects is solved according to the willingness of the representative agent to shift utility across time : if the elasticity of intertemporal substitution is sufficiently low, i.e. $\varepsilon > 1$, the first effect dominates and m_0 increases with d_0, and vice versa.

5 Conclusion

Some observers argue that renewable energy is not *manna from heaven*, since it requires specific equipment that relies on intensive use of exhaustible and finite mineral resources. We have shown that this empirical fact favors abundant and early investment in green capital for the production of renewable energy, given that minerals embedded in specialized green capital can be recycled, as opposed to fossil resources burned for energy production.

Our analysis has focused on the role of recycling in determining the optimal path of extraction of fossil and mineral resources, and the investment in green capital. However, we have considered a constant, costless and exogenous recycling process. It would be relevant to check how robust our argument is to relaxing these assumptions. On its own the issue of the optimal choice of the recycling rate is interesting, and more so in our context as it could affect the timing of investment in green capital.

We have adopted the normative approach of the benevolent social planner. However, it can be argued that market failures would lead to inefficient equilibria. Some market failures concern imperfect competition, both in the primary resource market and in the secondary one, when there is recycling (see Ba & Mahenc, 2019, and the literature review therein). Other potential failures concern the thinness of markets for specific minerals and the joint production of several mineral resources (Fizaine, 2015). Moreover, the decentralized investment in R&D directed at improvements in resource use efficiency or in recycling technology, may underpin potential dynamic inefficiencies (e.g. Zhou et al., 2018). Such market failures call for public intervention, raising the issue of their efficient design. We plan to study these extensions in future work.

It could also be interesting to investigate the role of the non-recycled share of used green capital. This cumulative waste involves a social cost to the extent that it may occupy scarce space or generate pollution in the absence of specific costly treatment. The social benefit of the development of recycling would therefore be confirmed : in addition to extending the life-cycle of the natural resource, therefore its use and the ability to generate energy from renewable sources, recycling reduces the amount of waste and its associated social cost.

Appendix

A Solutions of the infinite horizon

In the general case where we do not assume that there is an interval from $\underline{t}$ to $\bar{t}$ which corresponds to positive mineral extraction, the maximization program writes :

$$\max_{f_x,\, m_x} \sum_{x\geq 0} \frac{(1+\rho)^{-x}}{1-\varepsilon} \left(f_x^{\alpha} \left(K_{-1}\delta^{x+1} + \sum_{u=0}^{x} m_u \delta^{x-u} \right)^{1-\alpha} \right)^{1-\varepsilon}$$
$$+\lambda \left(F - \sum_{x\geq 0} f_x \right) + \nu \left(M - \sum_{x\geq 0} m_x \right) + \sum_{x\geq 0} \lambda_x f_x + \sum_{x\geq 0} \nu_x m_x$$

In the following, we simplify the notations by introducing : $\phi := \alpha(1-\varepsilon)$ and $\mu := (1-\alpha)(1-\varepsilon)$. To solve the program, we first assume in subsection A.1 that the positivity constraints always hold after a certain date $\underline{t}$, i.e. $\forall t \geq \underline{t},\ \lambda_t = \nu_t = 0$, which corresponds to an endless extraction of resources. Then in subsection A.2, we derive the optimal solution in the case where minerals are depleted at the initial period : $\forall t > 0,\ m_t = 0$. We show in Appendix B that these solutions are indeed optimal under the conditions given in Proposition 3.1.

A.1 Endless extraction

We assume a positive extraction of both resources starting at a date $\underline{t}$, before which only fossils are extracted. Using (2.6), the social planner's program rewrites :

$$\max \sum_{x=0}^{\underline{t}-1} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} \left(\delta^{x+1} K_{-1}\right)^{\mu} + \sum_{x\geq \underline{t}} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} K_x^{\mu} + \lambda \left(F - \sum_{x\geq 0} f_x \right) + \nu \left(M - \sum_{x\geq \underline{t}} m_x \right)$$

In the computations, we assume $\delta > 0$, but the solution extends to the limit cases $\delta = 0$. The log case $\varepsilon = 1$ is covered by the computations (only the program writes differently in this case).

The f.o.c.s are :

$$\begin{cases} (\partial f_t)_{t<\underline{t}} & \alpha f_t^{\phi-1} \left(\delta K_{-1}\right)^{\mu} = \lambda \left(\frac{1+\rho}{\delta^{\mu}}\right)^{t} \\ (\partial f_t)_{t\geq \underline{t}} & \alpha f_t^{\phi-1} K_t^{\mu} = \lambda (1+\rho)^{t} \\ (\partial m_t)_{t\geq \underline{t}} & \sum\limits_{x\geq t} f_x^{\phi} K_x^{\mu-1} \left(\frac{\delta}{1+\rho}\right)^{x} = \frac{\nu}{1-\alpha} \delta^{t} \end{cases}$$

where the last f.o.c. uses the definition of K_x in (2.6).

Subtracting the f.o.c. on m_{t+1} from the f.o.c. on m_t, we have

$$f_t^{\phi} K_t^{\mu-1} = \frac{\nu}{1-\alpha} (1-\delta)(1+\rho)^{t} \tag{A.1}$$

so that,

$$\forall t \geq \underline{t},\ K_t = \left(\frac{\nu}{1-\alpha} (1-\delta)(1+\rho)^{t} \right)^{\frac{1}{\mu-1}} f_t^{\frac{\phi}{1-\mu}} \tag{A.2}$$

Injecting this into the f.o.c. on f_t, and given that $\phi + \mu - 1 = -\varepsilon < 0$:

$$\begin{cases} \lambda = \alpha f_0^{\phi-1} (\delta K_{-1})^{\mu} \\ \forall t < \underline{t},\ f_t = \left(\frac{\lambda}{\alpha} \left(\frac{1+\rho}{\delta^{\mu}} \right)^t (\delta K_{-1})^{-\mu} \right)^{\frac{1}{\phi-1}} = f_0 \left(\frac{1+\rho}{\delta^{\mu}} \right)^{\frac{t}{\phi-1}} \\ \forall t \geq \underline{t},\ f_t = \left(\frac{\lambda}{\alpha} (1+\rho)^{\frac{t}{1-\mu}} \left(\frac{\nu}{1-\alpha} (1-\delta) \right)^{\frac{\mu}{1-\mu}} \right)^{\frac{1-\mu}{\phi+\mu-1}} \end{cases}$$

Defining $r := (1+\rho)^{\frac{1}{\phi+\mu-1}} = (1+\rho)^{-1/\varepsilon} < 1$ and $R := \left(\frac{1+\rho}{\delta^{\mu}} \right)^{\frac{1}{\phi-1}}$, this system gives :

$$\forall t < \underline{t},\ f_t = f_0 R^t \text{ and } \forall t \geq \underline{t},\ f_t = f_S r^t \tag{A.3}$$

Combining the f.o.c.s of $f_{\underline{t}}$ and $f_{\underline{t}-1}$, we have $f_S = f_0 \left(r\delta \frac{K_{-1}}{K_{\underline{t}}} \right)^{\frac{\mu}{\phi-1}}$, so that

$$\sum_{t\geq 0} f_t = f_0 \frac{1-R^{\underline{t}}}{1-R} + f_S \frac{r^{\underline{t}}}{1-r} = f_0 \left(\frac{1-R^{\underline{t}}}{1-R} + \left(r\delta \frac{K_{-1}}{K_{\underline{t}}} \right)^{\frac{\mu}{\phi-1}} \frac{r^{\underline{t}}}{1-r} \right) = f_S \left(\left(r\delta \frac{K_{-1}}{K_{\underline{t}}} \right)^{\frac{\mu}{1-\phi}} \frac{1-R^{\underline{t}}}{1-R} + \frac{r^{\underline{t}}}{1-r} \right)$$

The constraint (2.4) on recoverable resource of fossils gives $f_0 = F \left(\frac{1-R^{\underline{t}}}{1-R} + \left(r\delta \frac{K_{-1}}{K_{\underline{t}}} \right)^{\frac{\mu}{\phi-1}} \frac{r^{\underline{t}}}{1-r} \right)^{-1}$ and $f_S = F \left(\left(r\delta \frac{K_{-1}}{K_{\underline{t}}} \right)^{\frac{\mu}{1-\phi}} \frac{1-R^{\underline{t}}}{1-R} + \frac{r^{\underline{t}}}{1-r} \right)^{-1}$. Turning to the minerals, we have from (A.2) and (A.3), using (2.6) :

$$\begin{aligned} m_{\underline{t}} = K_{\underline{t}} - \delta^{\underline{t}+1} K_{-1} &= \left(\frac{\nu}{1-\alpha} (1-\delta) \right)^{\frac{1}{\mu-1}} f_S^{\frac{\phi}{1-\mu}} r^{\underline{t}} - \delta^{\underline{t}+1} K_{-1} \\ \forall t > \underline{t},\ m_t = K_t - \delta K_{t-1} &= \left(\frac{\nu}{1-\alpha} (1-\delta) \right)^{\frac{1}{\mu-1}} f_S^{\frac{\phi}{1-\mu}} r^{t-1} (r-\delta) =: K_{\underline{t}} r^{t-\underline{t}-1} (r-\delta) \end{aligned}$$

Lastly, $K_{\underline{t}}$ is determined by the transversality condition (2.7) on $(m_t)_{t\geq 0}$:

$$M = \sum_{t\geq \underline{t}} m_t = K_{\underline{t}} - \delta^{\underline{t}+1} K_{-1} + \sum_{t>\underline{t}} K_{\underline{t}} r^{t-\underline{t}-1} (r-\delta) = K_{\underline{t}} \frac{1-\delta}{1-r} - \delta^{\underline{t}+1} K_{-1}$$

i.e. $K_{\underline{t}} = \frac{1-r}{1-\delta} \left(M + \delta^{\underline{t}+1} K_{-1} \right)$. Finally, we obtain, with $r = (1+\rho)^{-\frac{1}{\varepsilon}}$ and $R = \left(\frac{1+\rho}{\delta^{\mu}} \right)^{\frac{1}{\phi-1}}$:

$$\begin{aligned} \forall t < \underline{t}, \quad f_t &= \left(\frac{1-R^{\underline{t}}}{1-R} + \left(\frac{r\delta (1-\delta) K_{-1}}{(1-r)(M+\delta^{\underline{t}+1} K_{-1})} \right)^{\frac{\mu}{\phi-1}} \frac{r^{\underline{t}}}{1-r} \right)^{-1} F \cdot R^t \\ \forall t \geq \underline{t}, \quad f_t &= \left(\left(\frac{r\delta (1-\delta) K_{-1}}{(1-r)(M+\delta^{\underline{t}+1} K_{-1})} \right)^{\frac{\mu}{1-\phi}} \frac{1-R^{\underline{t}}}{1-R} + \frac{r^{\underline{t}}}{1-r} \right)^{-1} F \cdot r^t \\ \forall t < \underline{t}, \quad m_t &= 0 \\ m_{\underline{t}} &= \frac{1-r}{1-\delta} M - \frac{r-\delta}{1-\delta} \delta^{\underline{t}+1} K_{-1} \\ \forall t > \underline{t}, \quad m_t &= \frac{1-r}{1-\delta} \left(M + \delta^{\underline{t}+1} K_{-1} \right) \left(1 - \frac{\delta}{r} \right) r^{t-\underline{t}} \end{aligned} \tag{A.4}$$

The positivity constraints hold for $\delta < r$ and for $\underline{t}$ such that $M > \delta^{\underline{t}+1} K_{-1} \frac{r-\delta}{1-r}$.

A.2 Immediate exhaustion

In this case, $\forall t > 0,\ m_t = 0$. We also assume that $\forall t,\ f_t > 0$ (see subsection B.1 for the justification). The objective is increasing in m_0, so it should be set to its maximum : $m_0 = M$. Then, the f.o.c. on f_t writes : $\alpha f_t^{\phi-1} M^\mu \delta^{\mu t} = \lambda (1+\rho)^t$, i.e. $f_t = \left(\frac{\lambda}{\alpha M^\mu}\left(\frac{1+\rho}{\delta^\mu}\right)^t\right)^{\frac{1}{\phi-1}}$. Defining $f_0 := \left(\frac{\lambda}{\alpha M^\mu}\right)^{\frac{1}{\phi-1}}$, we have : $\forall t \geq 0, \quad f_t = f_0 R^t$. To conclude, notice that according to Lemma C.1 in Appendix C.1 $\delta \geq r \Rightarrow R < 1$.[38] The transversality condition (2.4) must be saturated, as the program is increasing in f_t for all t. This gives $F = \sum_{t\geq 0} f_t = \frac{f_0}{1-R}$, thus $f_0 = F(1-R)$. Finally, we obtain : $\forall t \geq 0, \quad f_t = F(1-R)R^t$.

B Optimality of the solutions

Using the Karush-Kuhn-Tucker theorem in infinite horizon demonstrated in Appendix D (Corollary 4.1)[39], the optimality of the solution is straightforward. Indeed, the problem verifies the hypotheses of a weaker version of the theorem, that I describe on stackexchange.[40] Taking $X = \mathbb{R}_+^{\mathbb{N}}$ as the convex subset $X \subset \mathbb{R}^{\mathbb{N}}$, observing that the utility function and the constraints (formalizing the finiteness of the resources) are term-to-term differentiable (in f_k and m_k, $k \in \mathbb{N}$) and that the qualification condition holds (as any sequence of non-negative real numbers is in X), we make sure that the theorem applies and that the solution derived in section A is the unique optimal. Note that the standard Karush-Kuhn-Tucker theorem does not apply to this problem, as it relies on a finite number of variables and associated first order conditions.

In absence of the extension of the Karush-Kuhn-Tucker in infinite horizon, it is still possible to prove the optimality of the solution, but it takes about 10 pages instead of the previous paragraph. In this section, we detail this cumbersome demonstration of Proposition 3.1, as the extension of the Karush-Kuhn-Tucker has yet to become a commonly known result. We show in B.1 that it is never optimal to interrupt the extraction when $\delta < r$. Then we derive in B.2 the solution when minerals are depleted in a finite time and show that it is sub-optimal. Finally, we use all this to prove Proposition 3.1 in the case $\delta < r$ in B.3, and we treat the case $\delta \geq r$ in B.4.

B.1 Interruption of extraction

It is never optimal to let K or f be nil at any period because the marginal welfare goes to $+\infty$ when consumption is nil. Let us now show that for $\delta < r$, it is never optimal to interrupt mineral extraction, i.e. $\delta < r \implies \exists \underline{t}, \exists \bar{t} \geq \underline{t},\ m_t > 0 \iff t \in [\underline{t}, \bar{t}]$. Let $(m_t, f_t)_{t\geq 0}$ be an optimal solution and let T be such that $m_T > 0$ and such that $\{t > T | m_t > 0\} \neq \emptyset$. We define $\tau := \min_{t>T} \{t | m_t > 0\}$ in order to prove that $\tau = T+1$, i.e. that interruption of mineral extraction is suboptimal. Let us assume ad absurdo that $\tau \neq T+1$, so that $m_{T+1} = 0$ and $m_{\tau-1} = 0$. Then, as $\phi < 1$ and $\varepsilon > 0$,

38. Except in the degenerate case $\delta = 1 + \rho = R = 1$ for which there is no solution because the supremum of the objective is infinite and cannot be attained. However $\rho > 0$ by assumption.

39. This Appendix reproduces Bachir et al. (2019).

40. https ://economics.stackexchange.com/questions/20132/karush-kuhn-tucker-in-infinite-dimension/24665#24665

we deduce from $\delta < r$ using the definition of r :

$$1 > \left(\frac{\delta}{r}\right)^{(\tau-1-T)\frac{\varepsilon}{1-\phi}} = (1+\rho)^{\frac{\tau-1-T}{1-\phi}}\left(\frac{K_T}{K_T}\cdot\delta^{\tau-1-T}\right)^{\frac{\varepsilon}{1-\phi}}$$

$$= (1+\rho)^{\frac{\tau-1-T}{1-\phi}}\left(\frac{K_{\tau-1}}{K_T}\right)^{\frac{\mu\phi}{\phi-1}+1-\mu} = (1+\rho)^{(\tau-1-T)}\left(\frac{K_T}{K_{\tau-1}}\right)^{\mu-1}\left(\frac{f_T}{f_{\tau-1}}\right)^{\phi}$$

where we used the f.o.c.s on f_T and f_{T+1} to find the last equality. We thus have

$$(1-\alpha)(1+\rho)^{-T} f_T^{\phi} K_T^{\mu-1} < (1-\alpha)(1+\rho)^{-(\tau-1)} f_{\tau-1}^{\phi} K_{\tau-1}^{\mu-1}.$$

Besides, taking into account the non-negativity constraints $\nu_{\tau-1} \geq 0$ and $\nu_{T+1} \geq 0$ in equation A.1, we have :

$$(1-\alpha)(1+\rho)^{-T} f_T^{\phi} K_T^{\mu-1} = (1-\delta)\nu + \delta\nu_{T+1} \geq (1-\delta)\nu - \nu_{\tau-1} = (1-\alpha)(1+\rho)^{-(\tau-1)} f_{\tau-1}^{\phi} K_{\tau-1}^{\mu-1}$$

The last two inequalities contradict, so we deduce that $\tau = T+1$.

B.2 Exhaustion in a finite time

Let $\bar{t} > 0$ be the last period at which minerals are extracted. We assume in this subsection that extraction takes place from the initial period on. The program can be decomposed in two eras, during and after the extraction of minerals :

$$\max \sum_{x=0}^{\bar{t}} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} K_x^{\mu} + \sum_{x>\bar{t}} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} K_{\bar{t}}^{\mu} \delta^{\mu(x-\bar{t})} + \lambda\left(F - \sum_{x\geq 0} f_x\right) + \nu\left(M - \sum_{x\geq 0} m_x\right)$$

Using the f.o.c.s, one can derive the unique solution and write the inter-temporal welfare as follows, after defining with $a := \frac{1-r^{\bar{t}}}{1-r}(1-\delta)$ and $c = \left((1-\delta)\frac{R^{\bar{t}}}{1-R}\right)^{\frac{\phi-1}{\mu+\phi-1}} \delta^{\frac{\mu\bar{t}}{\mu+\phi-1}}$:[41]

$$\begin{aligned} W_{\bar{t}} &= \frac{f_0^{\phi} m_0^{\mu}}{1-\varepsilon} + \sum_{x=1}^{\bar{t}-1} (1+\rho)^{-x} \frac{f_x^{\phi} K_x^{\mu}}{1-\varepsilon} + (1+\rho)^{-\bar{t}} \frac{f_{\bar{t}}^{\phi} K_{\bar{t}}^{\mu}}{1-\varepsilon} + \sum_{x>\bar{t}} (1+\rho)^{-x} \frac{f_x^{\phi} K_{\bar{t}}^{\mu}}{1-\varepsilon} \delta^{\mu(x-\bar{t})} \\ &= \frac{1}{1-\varepsilon}\left(F^{\phi} \bar{M}^{\mu} (1-\delta)^{\phi-1} (a+c)^{1-\phi-\mu}\right) \end{aligned}$$

To show that extraction in a finite time is not optimal, we derive welfare with respect to the last period of extraction :

$$\frac{dW}{d\bar{t}} = W \frac{1-\phi-\mu}{a+c} \frac{d(a+c)}{d\bar{t}}$$

$$\frac{a+c}{1-\phi-\mu} \frac{1}{W} \frac{d\ln W}{d\bar{t}} = \frac{da}{d\bar{t}} + \frac{dc}{d\bar{t}} = -\ln(r)\, r^{\bar{t}} \left(\frac{1-\delta}{1-r} - \left(\frac{1-\delta}{1-R}\right)^{\frac{\phi-1}{\mu+\phi-1}}\right)$$

41. The detailed derivation is available in Appendix C.5.

It is optimal to delay the exhaustion of minerals if and only if $\frac{d\ln W}{d\bar{t}} > 0$. Notice that

$$\frac{1}{W}\frac{d\ln W}{d\bar{t}} > 0 \iff \frac{1-\delta}{1-r} > \left(\frac{1-\delta}{1-R}\right)^{\frac{\phi-1}{\mu+\phi-1}} \iff 1-R > (1-\delta)^{\frac{-\mu}{\phi-1}}(1-r)^{\frac{\mu+\phi-1}{\phi-1}}$$
$$\iff 1 - \frac{r^{\frac{\mu+\phi-1}{\phi-1}}}{\delta^{\frac{\mu}{\phi-1}}} > \left(\frac{1-\delta}{1-r}\right)^{\frac{\mu}{1-\phi}}(1-r)$$

Defining $v := \frac{\mu}{1-\phi}$ and $g_r(\delta) := 1 - \left(\frac{\delta}{r}\right)^v r - \left(\frac{1-\delta}{1-r}\right)^v (1-r)$, we have $\frac{1}{W}\frac{d\ln W}{d\bar{t}} > 0 \iff g_r(\delta) > 0$. Yet, $g_r^{'}(\delta) = v\left(\left(\frac{1-\delta}{1-r}\right)^{v-1} - \left(\frac{\delta}{r}\right)^{v-1}\right)$. For $v \in (0;1)$: $g_r^{'}(\delta) > 0 \iff \frac{1-\delta}{1-r} < \frac{\delta}{r} \iff r < \delta$ while for $v < 0$, the inverse is true : $g_r^{'}(\delta) > 0 \iff \delta < r$. In addition, $0 < \varepsilon < 1 \implies (1-\varepsilon) - \alpha(1-\varepsilon) < 1 - \alpha(1-\varepsilon) \implies v = \frac{(1-\alpha)(1-\varepsilon)}{1-\alpha(1-\varepsilon)} \in (0;1)$ while $\varepsilon > 1 \implies v < 0$ (in the limit case $\varepsilon = 1,\ g_r = 0$). For $\varepsilon < 1$, as $g_r(r) = 0$ and g_r is strictly decreasing below r and strictly increasing above r, we deduce that $\forall r,\ g_r \geq 0$ and that $\forall r, \forall \delta \neq r,\ g_r(\delta) > 0$. For $\varepsilon > 1$, the same reasoning shows that $\forall r,\ g_r \leq 0$ and that $\forall r, \forall\delta \neq r,\ g_r(\delta) < 0$. Given that $W > 0 \iff \varepsilon < 1$, $\varepsilon \neq 1 \implies \forall \delta \neq r,\ \frac{d\ln W}{dt} > 0$. The solutions extend to the log case $\varepsilon = 1$, but the formula of intertemporal welfare does not. Let us compare in this case $W_{\bar{t}+1}$ and $W_{\bar{t}}$.

$$\begin{aligned} W_{\bar{t}+1} - W_{\bar{t}} =& \sum_{t=0}^{\bar{t}} (1+\rho)^{-t} \ln\left(\left(\bar{M}\frac{1-r}{1-\delta}\right)^{1-\alpha} F^\alpha r^t\right) + \sum_{t>\bar{t}} (1+\rho)^{-t} \ln\left(\left(\bar{M}\delta^{t-\bar{t}-1} r^{\bar{t}+1}\right)^{1-\alpha} F^\alpha r^{\alpha t}\right) \\ &- \sum_{t=0}^{\bar{t}-1} (1+\rho)^{-t} \ln\left(\left(\bar{M}\frac{1-r}{1-\delta}\right)^{1-\alpha} F^\alpha r^t\right) - \sum_{t\geq\bar{t}} (1+\rho)^{-t} \ln\left(\left(\bar{M}\delta^{t-\bar{t}} r^{\bar{t}}\right)^{1-\alpha} F^\alpha r^{\alpha t}\right) \\ \frac{W_{\bar{t}+1} - W_{\bar{t}}}{1-\alpha} =& r^{\bar{t}} \ln\left(\frac{1-\delta}{1-r}\right) + \sum_{t>\bar{t}} r^t \ln\left(\frac{\delta}{r}\right) = r^{\bar{t}}\left(\ln\left(\frac{1-r}{1-\delta}\right) + \frac{r}{1-r}\ln\left(\frac{r}{\delta}\right)\right) \end{aligned}$$

Hence, for $\varepsilon = 1$, $W_{\bar{t}+1} > W_{\bar{t}} \iff h_r(\delta) := (1-r)\ln\left(\frac{1-r}{1-\delta}\right) + r\ln\left(\frac{r}{\delta}\right) > 0$. Yet, $h_r'(\delta) = \frac{1-r}{1-\delta} - \frac{r}{\delta} > 0 \iff \delta > r$ and $h_r(r) = 0$, so that $\forall \delta \neq r,\ h_r(\delta) > 0$. As a consequence, whatever the value of ε, it is always optimal to delay the end of mineral extraction and it is never optimal to exhaust minerals at a date $\bar{t} > 0$. Indeed, in the only case for which it is optimal to do so, $\delta = r$, all candidate solutions conflate to immediate exhaustion.

B.3 Case $\delta < r$

In this subsection, we call $\underline{t}$ the first period for which an optimal program's mineral extraction has a positive value : $\underline{t} := \min_{t\geq 0}\{m_t > 0\}$. Let us prove by induction on $\underline{t}$ that for all optimal solutions $(m_t,\ f_t)_{t\geq 0}$ such that $\underline{t}$ is the first period with positive mineral extraction, $t < \underline{t} \iff m_t = 0$. $t < \underline{t} \implies m_t = 0$ being true by definition, we only need to prove the reciprocal. In the base case $\underline{t} = 0$, $m_t = 0 \implies t \in \emptyset \implies t < \underline{t} = 0$ comes from the results of the three previous subsections that it is never optimal to stop or interrupt extraction. Then we turn to the inductive step, and we assume that the proposition has been proven for all $\underline{t} \leq n$, to show it in the case $\underline{t} = n+1$. Let $(m_t,\ f_t)_{t\geq 0}$ be a solution of the original program such that $\underline{t} = n+1$. Necessarily, $(m_t,\ f_t)_{t\geq 1}$ is optimal solution of the program starting at 1 with stock of resources $(M - m_0,\ F - f_0)$. Applying the induction on $(m_t,\ f_t)_{t\geq 1}$, we know that $\forall t \geq 1$, $(m_t = 0 \implies t < n+1)$. In addition, by definition of $\underline{t}$, $m_0 = 0$, so that $\forall t \geq 0$, $t < \underline{t} \iff m_t = 0$, which achieves the proof. Given that it is never optimal to interrupt or stop mineral extraction, the optimal extraction path is the one derived in Appendix A.

B.4 Case $\delta \geq r$

For $\delta > r$, and using the f.o.c.s on f_t and f_{t+1} [42], we have :

$$\forall t, \quad 1 < \left(\frac{\delta}{r}\right)^{\frac{\varepsilon}{1-\phi}} \leq (1+\rho)^{\frac{1}{1-\phi}} \left(\frac{m_{t+1}}{K_t} + \delta\right)^{\frac{\varepsilon}{1-\phi}}$$
$$= (1+\rho)^{\frac{-1}{\phi-1}} \left(\frac{K_{t+1}}{K_t}\right)^{\frac{\mu\phi}{\phi-1}+1-\mu} = (1+\rho)\left(\frac{K_t}{K_{t+1}}\right)^{\mu-1}\left(\frac{f_t}{f_{t+1}}\right)^{\phi}$$
$$\forall t, \quad (1+\rho)^{-t} f_t^{\phi} K_t^{\mu-1} > (1+\rho)^{-(t+1)} f_{t+1}^{\phi} K_{t+1}^{\mu-1}$$

Suppose ad absurdo that the optimal path $(m_t,\ f_t)_{t\geq 0}$ is such that there exists $T > 0$ such that $m_T > 0$. Let $\left(\tilde{m_t},\ \tilde{f_t}\right)_{t\geq 0}$ be an alternative path defined by $\forall t,\ \tilde{f_t} = f_t$, $\forall t \notin \{T;\ 0\}$, $\tilde{m_t} = m_t$, $\tilde{m_0} = m_0 + \eta$, $\tilde{m_T} = m_T - \eta$, for an arbitrary $\eta \in (0, m_T)$. Let us compare the welfares W_η and W given by $\left(\tilde{m},\ \tilde{f}\right)$ and $(m,\ f)$, respectively.

$$\tilde{W}_\eta = \frac{1}{1-\varepsilon}\left(\sum_{t<T}(1+\rho)^{-t} f_t^{\phi}\left(K_t + \eta\delta^t\right)^{\mu} + \sum_{t\geq T}(1+\rho)^{-t} f_t^{\phi}\left(K_t + \eta\left(\delta^t - \delta^{t-T}\right)\right)^{\mu}\right)$$
$$\underset{\eta\to 0^+}{=} \frac{1}{1-\varepsilon}\left(\sum_{t<T}(1+\rho)^{-t} f_t^{\phi}K_t^{\mu}\left(1 + \mu\eta\frac{\delta^t}{K_t}\right) + \sum_{t\geq T}(1+\rho)^{-t} f_t^{\phi}K_t^{\mu}\left(1+\mu\eta\frac{\delta^t - \delta^{t-T}}{K_t}\right)\right) + o(\eta)$$
$$\tilde{W}_\eta - W_\eta \underset{\eta\to 0^+}{=} \eta\alpha\left(\sum_{t\geq 0}\left((1+\rho)^{-t} f_t^{\phi}K_t^{\mu-1} - (1+\rho)^{-t-T} f_{t+T}^{\phi}K_{t+T}^{\mu-1}\right)\delta^t\right) + o(\eta)$$

From above, we know that $\forall t,\ (1+\rho)^{-t} f_t^{\phi}K_t^{\mu-1} > (1+\rho)^{-t-T} f_{t+T}^{\phi}K_{t+T}^{\mu-1}$, which implies that $\tilde{W}_\eta > W_\eta$.[43] This contradicts the optimality of $(m,\ f)$. We deduce that $\delta > r \implies \forall T > 0,\ m_T = 0$. Observing that for $\delta = r$ the unconstrained solution gives $\forall t > 0,\ m_t = 0$ concludes the proof.

C Other Appendices

C.1 Relations between the different rates

Lemme C.1. *For $\varepsilon < 1$, there are only three possible exclusive cases :*

$$\delta < R < r < \frac{1}{1+\rho} \quad \textit{or} \quad r < R < \min\left\{\frac{1}{1+\rho}, \delta\right\} \quad \textit{or} \quad \delta = R = r < \frac{1}{1+\rho}$$

whereas for $\varepsilon > 1$, the three possible cases are :

$$\max\left\{\delta, \frac{1}{1+\rho}\right\} < r < R \quad \textit{or} \quad \frac{1}{1+\rho} < R < r < \delta \quad \textit{or} \quad \delta = R = r > \frac{1}{1+\rho}$$

Finally, $\varepsilon = 1$ entails $r = R = \frac{1}{1+\rho} < 1$, with no relation on δ.
As $\delta < 1$, it follows that $\delta \geq r \implies R < 1$.

42. To equate the f.o.c.s on f_t we used the fact the $\forall t,\ f_t > 0$ shown in subsection B.1.
43. The argument does not rely on $\varepsilon \neq 1$, the limit case $\varepsilon = 1$ has not been presented for simplicity.

Démonstration. We always have $\delta < R \iff \delta^{\phi-1} > \frac{r^{\mu+\phi-1}}{\delta^{\mu}} \iff \delta < r$. For $\varepsilon < 1$, $\mu = (1-\alpha)(1-\varepsilon) > 0$, so that $r < R \iff r^{\phi-1} > \frac{r^{\mu+\phi-1}}{\delta^{\mu}} \iff \delta > r$. Ad absurdo, we also have that $\delta < R \implies R < r$ for $\varepsilon < 1$. In effect, suppose that $\delta < R$ and $r \leq R$. From the inequalities above (which are also valid as non-strict inequalities), we deduce two contradictory properties : $\delta < r$ and $\delta \geq r$. Reciprocally, $r \leq R \implies R \leq \delta$ for $\varepsilon < 1$. In addition, as $(\delta = r \iff r = R) \implies (\delta = r \iff R = \delta)$, there are only three possible exclusive cases in the case $\varepsilon < 1 : \delta < R < r \quad \vee \quad r < R < \delta \quad \vee \quad \delta = R = r$. Using a similar reasoning for $\varepsilon > 1$, and given that in this case $r < R \iff \delta < r$, we have $\varepsilon > 1 \implies \delta < r < R \quad \vee \quad R < r < \delta \quad \vee \quad \delta = R = r$. As $\delta < 1$, it follows that $\delta \geq r \implies R < 1$. Finally, observing that $R < \frac{1}{1+\rho} \iff \frac{1+\rho}{\delta^{\mu}} > (1+\rho)^{1-\phi} \iff (1+\rho)^{\phi} > \delta^{\mu} \iff (1+\rho)^{\alpha(1-\varepsilon)} > \delta^{(1-\alpha)(1-\varepsilon)} \iff \varepsilon < 1$ and $r < \frac{1}{1+\rho} \iff (1+\rho)^{1-\frac{1}{\varepsilon}} < 1 \iff \varepsilon < 1$ concludes the proof. □

C.2 Proof of Proposition 4.1

The problem is :.

$$\max \frac{1}{1-\varepsilon}\left[(A_0 f_0)^{\alpha}(B_0 m_0)^{1-\alpha}\right]^{1-\varepsilon} + \frac{1}{1-\varepsilon}\frac{1}{1+\rho}\left[(A_1 f_1)^{\alpha}(B_1(m_1+\delta m_0))^{1-\alpha}\right]^{1-\varepsilon} + \lambda(F - f_0 - f_1) + \nu(M - m_0 - m_1)$$

The f.o.c.s are

$$\begin{cases} (\partial f_0) & \alpha \frac{q_0^{1-\varepsilon}}{f_0} = \lambda \\ (\partial f_1) & \frac{\alpha}{1+\rho}\frac{q_1^{1-\varepsilon}}{f_1} = \lambda \\ (\partial m_0) & (1-\alpha)\frac{q_0^{1-\varepsilon}}{m_0} + \delta\frac{1-\alpha}{1+\rho}\frac{q_1^{1-\varepsilon}}{m_1+\delta m_0} = \nu \\ (\partial m_1) & \frac{1-\alpha}{1+\rho}\frac{q_1^{1-\varepsilon}}{m_1+\delta m_0} = \nu \end{cases}$$

Combining the last two

$$q_0^{1-\varepsilon} m_1 = \left(\frac{1-\delta}{1+\rho} q_1^{1-\varepsilon} - \delta q_0^{1-\varepsilon}\right) m_0$$

and using the exhaustion condition $m_0 + m_1 \leq M$ one gets m_0 and m_1 in (4.3) with the definition (4.2). Hence $m_1 > 0$, only for δ below the threshold $\widetilde{\delta} \equiv \frac{\widetilde{r}}{1+\widetilde{r}}$. Combining the first two f.o.c.s to get $f_1 = \frac{1}{1+\rho}\frac{q_1^{1-\varepsilon}}{q_0^{1-\varepsilon}} f_0$, then using the fossil resource exhaustion constraint $f_0 + f_1 \leq F$, one gets f_0 and f_1 in (4.3). As the Lagrangian is concave, the uniqueness stems from the Karush-Kuhn-Tucker theorem. These pace of resource use imply a specific pace of growth of energy consumption, given by (4.4). The gross discount factor is therefore :

$$\tilde{r} = \left[\left(\frac{A_1}{A_0}\right)^{\alpha}\left(\frac{B_1}{B_0}\right)^{1-\alpha}\right]^{\frac{1-\varepsilon}{\varepsilon}} (1+\rho)^{-\frac{1}{\varepsilon}} (1-\delta)^{(1-\alpha)\frac{1-\varepsilon}{\varepsilon}}$$

Notice that it is not affected by technological progress in the case of logarithmic utility, i.e. if $\varepsilon = 1$. The prospect of higher resource productivity ($A_1 > A_0$ or $B_1 > B_0$) increases the gross discount factor if the elasticity of intertemporal substitution is high enough ($1/\varepsilon > 1$), and vice versa. The input ratios are given by $\frac{f_0}{K_0} = (1-\delta)\frac{F}{M}$ and $\frac{f_1}{K_1} = \frac{F}{M}$, implying $\frac{\partial f_0/K_0}{\partial \delta} < 0$ but $\frac{\partial f_1/K_1}{\partial \delta} = 0$. Besides, $\frac{K_1}{K_0} = \frac{m_1+\delta m_0}{m_0} = \widetilde{r}(1-\delta) = (1-\delta)^{1+\frac{1-\alpha}{\varepsilon}(1-\varepsilon)}\left[\left(\frac{A_1}{A_0}\right)^{\alpha}\left(\frac{B_1}{B_0}\right)^{1-\alpha}\right]^{\frac{1-\varepsilon}{\varepsilon}}(1+\rho)^{-\frac{(1-\varepsilon)}{\varepsilon}-1}$, implying $\frac{\partial \frac{K_1}{K_0}}{\partial \delta} < 0$. Rewrite $m_0 = \frac{1}{(1-\delta)(1+\widetilde{r})}M$, to compute $\frac{\partial m_0}{\partial \delta} = -\frac{\frac{\partial(1-\delta)}{\partial \delta} + \frac{\partial(1-\delta)\widetilde{r}}{\partial \delta}}{(1-\delta)(1+\widetilde{r})} m_0 > 0$, since

$\frac{\partial(1-\delta)\tilde{r}}{\partial\delta} = -\frac{1-\alpha(1-\varepsilon)}{1-\delta}\tilde{r} < 0$. We can see that expectations of technological progress in both energy transformation technologies, postpone resource extraction, thus investment in green capital if the elasticity of intertemporal substitution is larger than unity : $\frac{\partial m_0}{\partial B_1} = -\frac{\frac{\partial(1-\delta)\tilde{r}}{\partial\delta}}{(1-\delta)(1+\tilde{r})} m_0 < 0 \Leftrightarrow \varepsilon < 1$.

C.3 Analysis of the CES case in Section 4.2

The problem is :

$$\max \frac{1}{1-\varepsilon}\left(\alpha f_0^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\, m_0^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}(1-\varepsilon)} + \frac{1}{1-\varepsilon}\frac{1}{1+\rho}\left(\alpha f_1^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\,(\delta m_0 + m_1)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}(1-\varepsilon)}$$
$$+ \lambda\,(F - f_0 - f_1) + \nu\,(M - m_0 - m_1)$$

with m_0, m_1, f_0, and $f_1 \geq 0$, and where $\sigma > 0$ (Cobb-Douglas production function for $\sigma = 1$) and $\varepsilon > 0$ (log utility for $\varepsilon = 1$).

A candidate interior solution satisfies the f.o.c.s

$$\begin{cases} (\partial f_0) & f_0^{\frac{\sigma-1}{\sigma}-1} q_0^{1-\varepsilon-\frac{\sigma-1}{\sigma}} = \frac{\lambda}{\alpha} \\ (\partial f_1) & \frac{1}{1+\rho} f_1^{\frac{\sigma-1}{\sigma}-1} q_1^{1-\varepsilon-\frac{\sigma-1}{\sigma}} = \frac{\lambda}{\alpha} \\ (\partial m_0) & m_0^{\frac{\sigma-1}{\sigma}-1} q_0^{1-\varepsilon-\frac{\sigma-1}{\sigma}} + \frac{\delta}{1+\rho}(\delta m_0 + m_1)^{\frac{\sigma-1}{\sigma}-1} q_1^{1-\varepsilon-\frac{\sigma-1}{\sigma}} = \frac{\nu}{1-\alpha} \\ (\partial m_1) & \frac{1}{1+\rho}(\delta m_0 + m_1)^{\frac{\sigma-1}{\sigma}-1} q_1^{1-\varepsilon-\frac{\sigma-1}{\sigma}} = \frac{\nu}{1-\alpha} \end{cases}$$

Combine the two f.o.c.s on f and the resource constraint $f_0 + f_1 \leq F$ to get f_0 and f_1 in (4.3), given the definition (4.5). Combine the two f.o.c.s on m and the resource constraint $m_0 + m_1 \leq M$, m_0 and m_1 in (4.6). An interior solution requires $m_1 > 0 \Leftrightarrow \left(\frac{q_1}{q_0}\right)^{1-\varepsilon\sigma}(1+\rho)^{-\sigma}(1-\delta)^{\sigma} > \delta$, which defines the threshold on δ specified in the main text.

In the case of an interior solution, the consumption growth ratio is computed from

$$\frac{q_1}{q_0} = \left(\frac{\alpha f_1^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\,(m_1 + \delta m_0)^{\frac{\sigma-1}{\sigma}}}{\alpha f_0^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\, m_0^{\frac{\sigma-1}{\sigma}}}\right)^{\frac{\sigma}{\sigma-1}}$$

substituting f_0 and f_1 from (4.3) and m_0 , m_1 from (4.6) to define the intertemporal consumption ratio as the solution of the implicit function (4.7).

C.4 Damages from fossil resources

Assuming that the resource constraint on fossils is not binding, the program writes :

$$\max \frac{\left(f_0^{\alpha} m_0^{1-\alpha}\right)^{1-\varepsilon}}{1-\varepsilon} - \frac{d_0}{\theta} f_0^{\theta} + \frac{1}{1+\rho}\left(\frac{\left(f_1^{\alpha}\,(m_1 + \delta m_0)^{1-\alpha}\right)^{1-\varepsilon}}{1-\varepsilon} - \frac{d_1}{\theta} f_1^{\theta}\right) + \nu\,(M - m_0 - m_1)$$

Using the definition $q_t \equiv f_t^{\alpha} K_t^{1-\alpha}$, the f.o.c.s are

$$\begin{cases} (\partial f_0) & \alpha q_0^{1-\varepsilon} = d_0 f_0^{\theta} \\ (\partial f_1) & \alpha q_1^{1-\varepsilon} = d_1 f_1^{\theta} \\ (\partial m_0) & (1-\alpha)\frac{q_0^{1-\varepsilon}}{m_0} + (1-\alpha)\frac{\delta}{1+\rho}\frac{q_1^{1-\varepsilon}}{m_1+\delta m_0} = \nu \\ (\partial m_1) & (1-\alpha)\frac{1}{1+\rho}\frac{q_1^{1-\varepsilon}}{m_1+\delta m_0} = \nu \end{cases}$$

The two f.o.c.s on m together with the exhaustion of minerals $m_1 + m_0 = M$, give the solutions in (4.3) for m_0 and m_1, with $\widetilde{r}$ defined in (4.2). It follows that $K_1 = \frac{\widetilde{r}}{1+\widetilde{r}}M$ and that an interior solution holds only if $\widetilde{r} > \frac{\delta}{1-\delta}$, i.e. $\delta < \widetilde{\delta} \equiv \frac{\widetilde{r}}{1+\widetilde{r}}$. The two f.o.c.s on f with the values of m_0 and m_1 in (4.3) give f_0 and f_1 in (4.9). Using these expressions one gets

$$\frac{q_1}{q_0} = \left[\left(\frac{d_0}{d_1}\right)^{\alpha} \left((1-\delta)\,\widetilde{r}\right)^{\theta(1-\alpha)}\right]^{\frac{1}{\theta-\alpha(1-\varepsilon)}}$$

Substituting (4.2) for $\widetilde{r}$ leads to (4.10).

Concerning the impact of a marginal increase of δ in the case of an interior solution, proceed as follows. For m_0, first combine (4.2) and (4.10) to compute $(1-\delta)\,\widetilde{r} = \left[\left(\frac{d_0}{d_1}\right)^{(1-\varepsilon)\alpha} \left(\frac{1-\delta}{1+\rho}\right)^{\theta-(1-\varepsilon)\alpha}\right]^{\frac{1}{\theta-(1-\varepsilon)[\alpha+\theta(1-\alpha)]}}$. Since $\theta - (1-\varepsilon)\left[\alpha + \theta\,(1-\alpha)\right] > 0$ and $\theta - (1-\varepsilon)\,\alpha > 0$, $\frac{\partial(1-\delta)\widetilde{r}}{\partial\delta} < 0$. Next from (4.3) write $m_0 = \frac{1}{(1-\delta)(1+\widetilde{r})}M$. We get $\frac{\partial m_0}{\partial\delta} = -\frac{\frac{\partial(1-\delta)}{\partial\delta}+\frac{\partial(1-\delta)\widetilde{r}}{\partial\delta}}{(1-\delta)(1+\widetilde{r})}m_0 > 0$. Given the exhaustion of minerals, the effect on m_1 runs in opposite direction. From (4.9), we have that $\frac{\partial f_0}{\partial\delta} = \frac{(1-\alpha)(1-\varepsilon)}{\theta-\alpha(1-\varepsilon)}\frac{f_0}{m_0}\frac{\partial m_0}{\partial\delta} > 0 \Leftrightarrow \varepsilon < 1$, hence $\partial\frac{f_0}{K_0}/\partial\delta = -\frac{1}{m_0^2}\left(f_0\frac{\partial m_0}{\partial\delta} - m_0\frac{\partial f_0}{\partial\delta}\right) = -\frac{f_0}{m_0^2}\left(\frac{\theta+\varepsilon-1}{\theta-\alpha(1-\varepsilon)}\right)\frac{\partial m_0}{\partial\delta} < 0$. Furthermore, $\frac{\partial f_1}{\partial\delta} = \frac{(1-\alpha)(1-\varepsilon)}{\theta-\alpha(1-\varepsilon)}\frac{f_1}{\widetilde{r}(1+\widetilde{r})}\frac{\partial\widetilde{r}}{\partial\delta} < 0$ since $\frac{\partial\widetilde{r}}{\partial\delta} < 0 \Leftrightarrow \varepsilon < 1$, and $\frac{f_1}{f_0} = \left(\left(\frac{d_0}{d_1}\right)^{\frac{\theta-(1-\varepsilon)\theta(1-\alpha)}{\theta-(1-\varepsilon)[\alpha+\theta(1-\alpha)]}}\left(\frac{1-\delta}{1+\rho}\right)^{\frac{\theta-(1-\varepsilon)\alpha}{\theta-(1-\varepsilon)[\alpha+\theta(1-\alpha)]}}\right)^{\frac{(1-\alpha)(1-\varepsilon)}{\theta-\alpha(1-\varepsilon)}}$, thus $\partial\frac{f_1}{f_0}/\partial\delta > 0 \Leftrightarrow \varepsilon > 1$. Finally $\partial\frac{f_1}{K_1}/\partial\delta = -\frac{\theta+\varepsilon-1}{\theta-\alpha(1-\varepsilon)}\frac{M}{\widetilde{r}}\frac{f_1}{K_1}\frac{\partial\widetilde{r}}{\partial\delta} > 0 \Leftrightarrow \varepsilon < 1$.

Concerning the impact of a marginal increase in first period damages, in the case of an interior solution, we have the following. From (4.9) , $\frac{\partial f_0}{\partial d_0} = \frac{f_0}{\theta-\alpha(1-\varepsilon)}\left((1-\alpha)\,(1-\varepsilon)\,\frac{\partial m_0/\partial d_0}{m_0} - \frac{1}{d_0}\right) < 0$. However from the expressions above, it follows that $\frac{\partial m_0}{\partial d_0} = -\frac{\partial(1-\delta)\widetilde{r}/\partial d_0}{(1-\delta)(1+\widetilde{r})}m_0 < 0 \Leftrightarrow \varepsilon < 1$. Finally, the signs of the derivatives are summarized in Table C.1.

TABLE C.1 – Signs of derivatives of the solutions with respect to the parameters

	m_0	m_1	f_0	f_1	$\frac{f_0}{K_0}$	$\frac{f_1}{K_1}$
δ	$+$	$-$	$- \iff \varepsilon > 1$	$-$	$-$	$- \iff \varepsilon > 1$
d_0	$+ \iff \varepsilon > 1$	$- \iff \varepsilon > 1$	$\varepsilon < 1 \implies -$	$+$	$\varepsilon > 1 \implies -$	$+ \iff \varepsilon > 1$
d_1	$- \iff \varepsilon > 1$	$+ \iff \varepsilon > 1$	$+$	$\varepsilon < 1 \implies -$	$+ \iff \varepsilon > 1$	$\varepsilon > 1 \implies -$

C.5 Derivation of $W_{\bar{t}}$ in Appendix B.2

The problem is

$$\max \sum_{x=0}^{\bar{t}} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} K_x^{\mu} + \sum_{x>\bar{t}} \frac{(1+\rho)^{-x}}{1-\varepsilon} f_x^{\phi} K_{\bar{t}}^{\mu} \delta^{\mu(x-\bar{t})} + \lambda\left(F - \sum_{x\geq 0} f_x\right) + \nu\left(M - \sum_{x\geq 0} m_x\right)$$

and the f.o.c.s are :

$$\begin{cases} (\partial f_t)_{t\leq\bar{t}} & \alpha f_t^{\phi-1} K_t^{\mu}\,(1+\rho)^{-t} = \lambda \\ (\partial f_t)_{t>\bar{t}} & \alpha f_t^{\phi-1} K_{\bar{t}}^{\mu} \delta^{\mu(t-\bar{t})}\,(1+\rho)^{-t} = \lambda \\ (\partial m_t)_{t\leq\bar{t}} & (1-\alpha)\sum\limits_{x=t}^{\bar{t}} (1+\rho)^{-x} f_x^{\phi} K_x^{\mu-1} \delta^{x-t} + (1-\alpha)\sum\limits_{x>\bar{t}} (1+\rho)^{-x} f_x^{\phi} K_{\bar{t}}^{\mu-1} \delta^{\mu(x-\bar{t})+\bar{t}-t} = \nu \end{cases}$$

The f.o.c. on m_{t+1} can be expressed as follows for $t < \bar{t}$:

$$\frac{1-\alpha}{\delta}\sum_{x=t}^{\bar{t}}(1+\rho)^{-x}\, f_x^{\phi}K_x^{\mu-1}\delta^{x-t} - (1-\alpha)(1+\rho)^{-t}\,\frac{f_t^{\phi}K_t^{\mu-1}}{\delta} + \frac{1-\alpha}{\delta}\sum_{x>\bar{t}}(1+\rho)^{-x}\, f_x^{\phi}K_{\bar{t}}^{\mu-1}\delta^{\mu(x-\bar{t})+\bar{t}-t} = \nu$$

Then, $\forall t < \bar{t}$, $\frac{(\partial m_t)}{\delta} - (\partial m_{t+1})$ yields $(1-\alpha)(1+\rho)^{-t}\, f_t^{\phi}K_t^{\mu-1} = \nu(1-\delta)$, so that

$$\forall t < \bar{t}, \quad K_t = \left(\frac{\nu}{1-\alpha}(1-\delta)(1+\rho)^t\right)^{\frac{1}{\mu-1}} f_t^{\frac{\phi}{1-\mu}} \tag{C.1}$$

Furthermore, $(\partial m_{\bar{t}})$ gives $(1-\alpha)\sum_{x\geq\bar{t}}(1+\rho)^{-x}\, f_x^{\phi}K_{\bar{t}}^{\mu-1}\delta^{\mu(x-\bar{t})} = \nu$, i.e.

$$K_{\bar{t}} = \left(\frac{1-\alpha}{\nu}\sum_{x\geq\bar{t}}(1+\rho)^{-x}\, f_x^{\phi}\delta^{\mu(x-\bar{t})}\right)^{\frac{1}{1-\mu}} \tag{C.2}$$

Injecting (C.1) into the f.o.c. on f_t yields $\forall t < \bar{t}$,

$$\begin{aligned}\lambda &= \alpha f_t^{\phi-1+\frac{\phi\mu}{1-\mu}}\left(\frac{\nu}{1-\alpha}(1-\delta)\right)^{\frac{\mu}{\mu-1}}(1+\rho)^{\frac{1}{\mu-1}t}\\ &= \alpha f_0^{\phi-1+\frac{\phi\mu}{1-\mu}}\left(\frac{\nu}{1-\alpha}(1-\delta)\right)^{\frac{\mu}{\mu-1}}\end{aligned}$$

i.e.

$$f_t = \left(\frac{\lambda}{\alpha}(1+\rho)^{\frac{1}{1-\mu}t}\left(\frac{\nu}{1-\alpha}(1-\delta)\right)^{\frac{\mu}{1-\mu}}\right)^{\frac{1-\mu}{\phi+\mu-1}}$$

Defining $r := (1+\rho)^{\frac{1}{\phi+\mu-1}} < 1$ and $f_< := \left(\frac{\lambda}{\alpha}\right)^{\frac{1-\mu}{\phi+\mu-1}}\left(\frac{\nu}{1-\alpha}(1-\delta)\right)^{\frac{\mu}{\phi+\mu-1}}$, we have :

$$\forall t < \bar{t}, \quad f_t = f_< r^t \tag{C.3}$$

For $t > \bar{t}$, the f.o.c. on f_t yields :[44]

$$f_t = \left(\frac{\lambda\delta^{\mu\bar{t}}}{\alpha K_{\bar{t}}^{\mu}}\left(\frac{1+\rho}{\delta^{\mu}}\right)^t\right)^{\frac{1}{\phi-1}}$$

Defining $R := \left(\frac{1+\rho}{\delta^{\mu}}\right)^{\frac{1}{\phi-1}}$ and $f_> := \left(\frac{\lambda\delta^{\mu\bar{t}}}{\alpha K_{\bar{t}}^{\mu}}\right)^{\frac{1}{\phi-1}}$, we have :

$$\forall t > \bar{t}, \quad f_t = f_> R^t \tag{C.4}$$

In the following, we assume that $R < 1$. Combining the f.o.c. on $f_{\bar{t}}$ with the f.o.c. on $f_{\bar{t}+1}$:

44. For $\delta = 0$, marginal welfare goes to infinity for each $t > \bar{t}$, as $K_t = 0$. Hence, it is obviously suboptimal not to extract at every period in this case. In the following, we assume $\delta > 0$.

$f_{\bar{t}}^{\phi-1}(1+\rho) = f_{\bar{t}+1}^{\phi-1}\delta^{\mu} = f_{>}^{\phi-1}R^{(\phi-1)(\bar{t}+1)}\delta^{\mu}$. This gives $f_{\bar{t}}$:

$$f_{\bar{t}} = f_{>}R^{\bar{t}} \tag{C.5}$$

The transversality condition on fossils gives :

$$F = f_{<}\sum_{t=0}^{\bar{t}-1} r^t + f_{>}\sum_{t\geq\bar{t}} R^t = f_{<}\frac{1-r^{\bar{t}}}{1-r} + f_{>}\frac{R^{\bar{t}}}{1-R} \tag{C.6}$$

Injecting (C.3) into (C.1) for $t < \bar{t}$, we obtain $K_t = \left(\frac{\nu}{1-\alpha}(1-\delta)(1+\rho)^t\right)^{\frac{1}{\mu-1}} f_{<}^{\frac{\phi}{1-\mu}} r^{\frac{\phi}{1-\mu}t}$ so that $K_0 = \left(\frac{\nu}{1-\alpha}(1-\delta)\right)^{\frac{1}{\mu-1}} f_{<}^{\frac{\phi}{1-\mu}}$. Hence :

$$\forall t < \bar{t}, \quad K_t = K_0(1+\rho)^{\frac{t}{\mu-1}} r^{\frac{\phi}{1-\mu}t} = K_0(1+\rho)^{\frac{1}{\phi+\mu-1}t} = K_0 r^t \tag{C.7}$$

which gives

$$\forall t \in [1, \bar{t}-1], \quad m_t = K_t - \delta K_{t-1} = K_0\left(1-\frac{\delta}{r}\right)r^t$$

The transversality condition on minerals gives :

$$M = \sum_{t=0}^{\bar{t}} m_t = K_0 - \delta K_{-1} + \sum_{t=1}^{\bar{t}-1} K_0 r^t\left(1-\frac{\delta}{r}\right) + m_{\bar{t}}$$
$$m_{\bar{t}} = M + \delta K_{-1} - K_0\left(1+(r-\delta)\frac{1-r^{\bar{t}-1}}{1-r}\right)$$

Hence,

$$K_{\bar{t}} = m_{\bar{t}} + \delta K_{\bar{t}-1} = M + \delta K_{-1} - K_0\left(1+(r-\delta)\frac{1-r^{\bar{t}-1}}{1-r}\right) + \delta K_0 r^{\bar{t}-1}$$
$$= M + \delta K_{-1} - K_0\frac{1-r^{\bar{t}}}{1-r}(1-\delta) = \bar{M} - aK_0 \tag{C.8}$$

with $a := \frac{1-r^{\bar{t}}}{1-r}(1-\delta)$ and $\bar{M} := M + \delta K_{-1}$.

Using (C.3) in the f.o.c. on f_0 together with the f.o.c. on $f_{\bar{t}+1}$:

$$f_{<}^{\phi-1}K_0^{\mu} = \delta^{-\mu\bar{t}} f_{>}^{\phi-1}K_{\bar{t}}^{\mu}$$

Injecting (C.6) and (C.8) into this : [45]

$$f_{<}^{\frac{\phi-1}{\mu}} f_{>}^{-\frac{\phi-1}{\mu}} K_0 = \delta^{-\bar{t}}\left(\bar{M} - aK_0\right)$$
$$f_{<}^{\frac{\phi-1}{\mu}}\left(\left(F - f_{<}\frac{1-r^{\bar{t}}}{1-r}\right)\frac{1-R}{R^{\bar{t}}}\right)^{-\frac{\phi-1}{\mu}} = \delta^{-\bar{t}}\left(\frac{\bar{M}}{K_0} - a\right) \tag{C.9}$$

45. In the log case, $\varepsilon = 1$, $R = r < 1$, $f_{<} = f_{>}$ and the solution derived below extends to this case.

The f.o.c. on $m_{\bar{t}}$ gives :

$$\begin{aligned}(1-\alpha)(1+\rho)^{-\bar{t}} f_{\bar{t}}^{\phi} K_{\bar{t}}^{\mu-1} + (1-\alpha)\sum_{x>\bar{t}}(1+\rho)^{-x} f_x^{\phi} K_{\bar{t}}^{\mu-1}\delta^{\mu(x-\bar{t})} &= (1-\alpha)\sum_{x\geq\bar{t}} R^x f_>^{\phi} K_{\bar{t}}^{\mu-1}\delta^{-\mu\bar{t}} \\ &= (1-\alpha) f_>^{\phi} K_{\bar{t}}^{\mu-1}\delta^{-\mu\bar{t}}\frac{R^{\bar{t}}}{1-R} = \nu\end{aligned}$$

Using $\frac{K_0^{\mu-1} f_<^{\phi}}{1-\delta} = \frac{\nu}{1-\alpha}$ from the expression of K_0, we have from last equation :

$$f_>^{\phi} K_{\bar{t}}^{\mu-1}\delta^{-\mu\bar{t}}\frac{R^{\bar{t}}}{1-R} = \frac{K_0^{\mu-1} f_<^{\phi}}{1-\delta} \tag{C.10}$$

Injecting (C.6) and (C.8) into this :

$$\left(\left(F - f_<\frac{1-r^{\bar{t}}}{1-r}\right)\frac{1-R}{R^{\bar{t}}}\right)^{\frac{\phi}{\mu-1}}\left(\frac{\bar{M}}{K_0} - a\right) = \left(\frac{f_<^{\phi}}{1-\delta}\frac{1-R}{R^{\bar{t}}}\delta^{\mu\bar{t}}\right)^{\frac{1}{\mu-1}} \tag{C.11}$$

Combining this with (C.9) we have an equation in $f_<$:

$$\begin{aligned} f_<^{\frac{\phi-1}{\mu}-\frac{\phi}{\mu-1}}\left(\left(F - f_<\frac{1-r^{\bar{t}}}{1-r}\right)\frac{1-R}{R^{\bar{t}}}\right)^{\frac{\phi}{\mu-1}-\frac{\phi-1}{\mu}} &= \delta^{-\bar{t}}\left(\frac{\delta^{\mu\bar{t}}}{1-\delta}\frac{1-R}{R^{\bar{t}}}\right)^{\frac{1}{\mu-1}} \\ \left(\frac{F}{f_<} - \frac{1-r^{\bar{t}}}{1-r}\right)\frac{1-R}{R^{\bar{t}}} &= b^{\mu} \end{aligned} \tag{C.12}$$

where $b := \left(\frac{\delta^{\bar{t}}}{1-\delta}\frac{1-R}{R^{\bar{t}}}\right)^{\frac{1}{\mu+\phi-1}}$.

$$f_< = \left(b^{\mu}\frac{R^{\bar{t}}}{1-R} + \frac{1-r^{\bar{t}}}{1-r}\right)^{-1} F = \frac{1-\delta}{a+c}F \tag{C.13}$$

where :

$$c := b^{\mu}\frac{R^{\bar{t}}}{1-R}(1-\delta) = \left(\frac{1-\delta}{\delta^{\bar{t}}}\frac{R^{\bar{t}}}{1-R}\right)^{\frac{-\mu}{\mu+\phi-1}}\frac{R^{\bar{t}}}{1-R}(1-\delta) = \left((1-\delta)\frac{R^{\bar{t}}}{1-R}\right)^{\frac{\phi-1}{\mu+\phi-1}}\delta^{\frac{\mu\bar{t}}{\mu+\phi-1}}$$

Injecting (C.12) into (C.9) (at the second line), we deduce K_0 :

$$\begin{aligned} K_0 &= \bar{M}\left(f_<^{\frac{\phi-1}{\mu}}\left(\left(F - f_<\frac{1-r^{\bar{t}}}{1-r}\right)\frac{1-R}{R^{\bar{t}}}\right)^{-\frac{\phi-1}{\mu}}\delta^{\bar{t}} + a\right)^{-1} \\ &= \frac{\bar{M}}{b^{1-\phi}\delta^{\bar{t}} + a} = \frac{\bar{M}}{a+c} \end{aligned} \tag{C.14}$$

Injecting (C.14) into (C.8), we deduce $K_{\bar{t}}$:

$$K_{\bar{t}} = \frac{c\bar{M}}{a+c} = cK_0 = b^{1-\phi}\delta^{\bar{t}}K_0 \tag{C.15}$$

We get $f_>$ from (C.6) and (C.13) :

$$f_> = \frac{1-R}{R^{\bar{t}}}\left(F - f_< \frac{1-r^{\bar{t}}}{1-r}\right) = b^\mu f_< \tag{C.16}$$

Finally, the inter-temporal welfare writes :

$$\begin{aligned}
W_{\bar{t}} &= \frac{f_0^\phi m_0^\mu}{1-\varepsilon} + \sum_{x=1}^{\bar{t}-1}(1+\rho)^{-x}\frac{f_x^\phi K_x^\mu}{1-\varepsilon} + (1+\rho)^{-\bar{t}}\frac{f_{\bar{t}}^\phi K_{\bar{t}}^\mu}{1-\varepsilon} + \sum_{x>\bar{t}}(1+\rho)^{-x}\frac{f_x^\phi K_{\bar{t}}^\mu}{1-\varepsilon}\delta^{\mu(x-\bar{t})} \\
&= \frac{1}{1-\varepsilon}\left(f_<^\phi K_0^\mu + \sum_{x=1}^{\bar{t}-1}(1+\rho)^{-x} f_<^\phi r^{\phi x} K_0^\mu r^{\mu x} + (1+\rho)^{-\bar{t}} f_>^\phi R^{\phi \bar{t}} K_{\bar{t}}^\mu + \sum_{x>\bar{t}}(1+\rho)^{-x} f_>^\phi R^{\phi x} K_{\bar{t}}^\mu \delta^{\mu(x-\bar{t})}\right) \\
&= \frac{1}{1-\varepsilon}\left(f_<^\phi K_0^\mu \frac{1-\left(\frac{r^{\phi+\mu}}{1+\rho}\right)^{\bar{t}}}{1-\frac{r^{\phi+\mu}}{1+\rho}} + (1+\rho)^{-\bar{t}} b^{\mu\phi} f_<^\phi R^{\phi\bar{t}} b^{\mu(1-\phi)} \delta^{\mu\bar{t}} K_0^\mu + f_>^\phi K_{\bar{t}}^\mu \delta^{-\mu\bar{t}}\frac{R^{\bar{t}+1}}{1-R}\right) \\
&= \frac{1}{1-\varepsilon}\left(f_<^\phi K_0^\mu\left(\frac{1-\left(\frac{r^{\phi+\mu}}{1+\rho}\right)^{\bar{t}}}{1-\frac{r^{\phi+\mu}}{1+\rho}} + b^\mu \delta^{\mu\bar{t}}\left(R^{\phi\bar{t}}(1+\rho)^{-\bar{t}} + \delta^{-\mu\bar{t}}\frac{R^{\bar{t}+1}}{1-R}\right)\right)\right) \\
&= \frac{1}{1-\varepsilon}\left(F^\phi \bar{M}^\mu\left(\frac{1-\delta}{a+c}\right)^\phi (a+c)^{-\mu}\left(\frac{1-r^{\bar{t}}}{1-r} + b^\mu \frac{R^{\bar{t}}}{1-R}\right)\right) \\
&= \frac{1}{1-\varepsilon}\left(F^\phi \bar{M}^\mu (1-\delta)^{\phi-1}(a+c)^{1-\phi-\mu}\right)
\end{aligned}$$

C.6 Welfare analysis

In case $(2.a)$ of Proposition 3.1 the inter-temporal welfare takes the value :

$$\begin{aligned}
W_\infty &= \sum_{t\geq 0}(1+\rho)^{-t}\frac{f_t^\phi K_t^\mu}{1-\varepsilon} \\
&= \frac{f_0^\phi m_0^\mu}{1-\varepsilon} + \sum_{t\geq 1}(1+\rho)^{-t}\frac{f_t^\phi K_t^\mu}{1-\varepsilon} \\
&= \frac{f_0^\phi m_0^\mu}{1-\varepsilon} + \frac{f_0^\phi m_0^\mu}{1-\varepsilon}\sum_{t\geq 1}\left(\frac{r^{\phi+\mu}}{1+\rho}\right)^t \\
&= \frac{f_0^\phi m_0^\mu}{1-\varepsilon}\left(1+\frac{r}{1-r}\right)
\end{aligned} \tag{C.17}$$

In the previous computations, we used $\frac{r^{\phi+\mu}}{1+\rho} = (1+\rho)^{\frac{\phi+\mu}{\phi+\mu-1}-1} = (1+\rho)^{\frac{1}{\phi+\mu-1}} = r$. It follows that :

$$\frac{\partial W_\infty}{\partial \delta} = F^\phi M^\mu (1-r)^{\phi+\mu-1}(1-\alpha)(1-\delta)^{-\mu-1} > 0$$

In case (1) of Proposition 3.1 the inter-temporal welfare takes the value :

$$\begin{aligned} W_0 &= \sum_{t\geq 0} \frac{(1+\rho)^{-t}}{1-\varepsilon} f_t^{\phi} m_0^{\mu} \delta^{\mu t} \\ &= \frac{1}{1-\varepsilon} M^{\mu} F^{\phi} (1-R)^{\phi} \sum_{t\geq 0} (1+\rho)^{-t} \delta^{\mu t} R^{\phi t} \\ &= \frac{1}{1-\varepsilon} M^{\mu} F^{\phi} (1-R)^{\phi-1} \end{aligned}$$

In the computations, we used $(1+\rho)^{-1} \delta^{\mu} R^{\phi} = R^{1-\phi} R^{\phi} = R$. It follows that

$$\begin{aligned} \frac{\partial W_0}{\partial \delta} &= \frac{1-\phi}{1-\varepsilon} M^{\mu} F^{\phi} (1-R)^{\phi-2} \frac{\partial R}{\partial \delta} \\ &= \begin{cases} (+)\cdot(+) > 0 \text{ for } \varepsilon \in (0,1) \\ (-)\cdot(-) > 0 \text{ for } \varepsilon > 1 \end{cases} \end{aligned}$$

Welfare increases with δ also in case $(2.b)$ since it is a mix of the two cases above.

D Karush-Kuhn-Tucker in infinite horizon [46]

The following abstract presents our main results in a simplified way.

Abstract To extend the Karush-Kuhn-Tucker to series (while the original version requires a finite number of variables), we introduce the notion of finite determination. We say that a real-valued function f on a vector space E of countable dimension [47] is finitely determined if for all $a \in E : \forall x = (x_k)_{k\in\mathbb{N}} \in E, \quad f(x) = \lim_{n\to+\infty} f((x_1, \ldots, x_n, a_{n+1}, a_{n+2}, \ldots))$ (Definition 1.1). We show that for convex functions defined on Banach spaces with a Schauder basis [48] (like $\mathbb{R}^{\mathbb{N}}$), the notion of continuity coincides with that of finite determination (Corollary 2.2). We then prove that a finitely determined convex function f attains its infimum where its directional derivatives [49] (along the directions of the Schauder basis) are nil : $f(a) = \inf f \Leftrightarrow \forall k \in \mathbb{N}, f'(a; e_k) = 0$ (Theorem 3.1). We further show that for f convex and continuous at a, $f'(a; e_n)$ exists for all $n \in \mathbb{N}$ if and only if f is Gateaux differentiable [50] at a (Corollary 3.2). As a corollary, we prove that the Karush-Kuhn-Tucker theorem extends to series : for a convex continuous function f maximized on a convex subset of $\mathbb{R}^{\mathbb{N}}$ under a finite number of constraints, if x^* is a solution of the Lagrangian, then x^* is an optimum (Corollary 4.2).

Contributions Adrien Fabre gave the idea of the paper. Mohammed Bachir wrote most of the paper. Sebastián Tapia García refined the analysis of finite determination.

46. Joint with Mohammed Bachir & Sebastián Tapia García.
47. More precisely, E should be a topological vector space equipped with a biorthogonal system.
48. I.e. spaces E with a topological basis $(e_k)_{k\in\mathbb{N}}$ such that each element $x \in E$ can be written as a unique series of the form $x = \sum_{k\in\mathbb{N}} x_k e_k$.
49. f admits a directional derivative in the direction $d \in E$ if $f'(a; d) = \lim_{t\to 0^+} \frac{f(a+td)-f(a)}{t}$ exists in $\mathbb{R}$.
50. f is said Gateaux differentiable at a if the directional derivative exists for all directions $d \in E$ and if $Df(a) : d \mapsto f'(a; d)$ is a continuous linear map.

1 Introduction

Let E be a topological vector space over the field $\mathbb{R}$ and E^* its topological dual. Let (e_n) be a linearly independent family of elements of E and (e_n^*) be a family of elements of E^*. The pair (e_n, e_n^*) is said to be a biorthogonal system if $\langle e_n^*, e_n\rangle = 1$ for all $n \in \mathbb{N}$ and $\langle e_n^*, e_k\rangle = 0$ if $n \neq k$. Furthermore, (e_n, e_n^*) it is called fundamental if $E = \overline{\text{span}}(e_n : \ n \in \mathbb{N})$. The linear mappings $P_k : E \longrightarrow E$ are defined for all $k \in \mathbb{N}$ as follows

$$x \overset{P_k}{\longrightarrow} P_k(x) = \sum_{n=0}^{k} \langle e_n^*, x\rangle e_n.$$

A well known result asserts that each Banach space E contains a biorthogonal system $(e_n, e_n^*)_n$. Moreover, whenever E is separable there always exists a fundamental biorthogonal system, see Ovsepian & Pełczyński (1975).

Throughout the manuscript, we assume that the topological vector space E is equipped with a biorthogonal system (e_n, e_n^*). For further information about biorthogonal systems, we refer to Albiac & Kalton (2016), Fabian et al. (2011), Fabian et al. (2013), Dieudonné (1953) and Marchenko (2014).

Definition 1.1 We say that $f : E \to \mathbb{R}$ is finitely determined by the biorthogonal system (e_n, e_n^*) with respect to $a \in E$ if we have :

$$f(x) = \lim_{n\to+\infty} f(a + P_n(x - a)), \ \forall\ x \in E,$$

If the above equality is satisfied with respect to all $a \in E$, then we say that f is finitely determined by the biorthogonal system (e_n, e_n^*). We say that f is inf-finitely determined by the biorthogonal system (e_n, e_n^*) with respect to $a \in E$ if we have :

$$f(x) \geq \inf_{n\in\mathbb{N}} f(a + P_n(x - a)), \ \forall\ x \in E,$$

If the above inequality is satisfied with respect to all $a \in E$, then we say that f is inf-finitely determined.

When there is no confusion with the related biorthogonal system, we will simply say that f is finitely determined (resp. inf-finitely determined) at a or with respect to a.

Clearly, every finitely determined function is inf-finitely determined. The aim of this paper is to study the notions of finitely determined and inf-finitely determined function and their applications to optimization. The motivation behind the study of these notions, lies in the following simple observations :

(1) If f is inf-finitely determined (not necessarily convex), then f has a global minimum at $\bar{x} = 0$ (we take $\bar{x} = 0$ for simplicity) if and only if the restriction $f_{|P_k(E)}$ has a global minimum at 0 for each $k \in \mathbb{N}$, where $P_k(E)$ denotes the image of E under the linear mapping P_k. Since $P_k(E)$ is of finite dimension for each $k \in \mathbb{N}$, the terminology of *finitely determined function* is motivated.

(2) Let $E = l^\infty(\mathbb{N})$ the Banach space of bounded sequences. We set the biorthogonal system (e_n, e_n^*) given by the canonical basis (e_n) of $c_0(\mathbb{N})$, seen as a subspace of E, and the respective

coordinate functionals $(e_n^*) \subset E^*$. Let $p : l^\infty(\mathbb{N}) \to \mathbb{R}$ defined by $p(x) = \limsup_n |x_n|$. We know from Phelps (1993, Example 1.21) that p is nowhere Gateaux differentiable. On the other hand, clearly, p is convex and inf-finitely determined with respect to each point a of $c_0(\mathbb{N})$ (p is also a norm continuous seminorm). Moreover, the directional derivative with respect to the canonical basis (e_n) of $l^\infty(\mathbb{N})$, exists and is equal to 0 at each point of $l^\infty(\mathbb{N})$ (see Example 2.1), that is, for all $x \in l^\infty(\mathbb{N})$ and all $n \in \mathbb{N}$,

$$p'(x; e_n) := \lim_{\substack{t \to 0 \\ t \neq 0}} \frac{1}{t}\Big(p(x + te_n) - p(x)\Big) = 0 \qquad (\star)$$

We then notice trivially, that p has a minimum at a point a iff $a \in c_0(\mathbb{N})$. Also, p is inf-finitely determined with respect a iff $a \in c_0(\mathbb{N})$. The question in this paper is : is it true that every convex function $f : l^\infty(\mathbb{N}) \to \mathbb{R}$ which is inf-finitely determined with respect to some point $x_0 \in l^\infty(\mathbb{N})$ and satisfies the equation $(\star)$ at x_0 (weaker than Gateaux differentiability), has necessarily a minimum at this point ? We answer this question positively, even in a more general framework (Theorem 3.1). Thus, for inf-finitely determined function with respect to x, the criterion $(\star)$ is sufficient to characterize a minimum at x, and the stronger assumption of Gateaux differentiability can be relaxed.

We say that (e_n) is a topological basis (or Schauder basis) of E if for each $x \in E$, there exists a unique sequence (a_n) of real number such that $x = \sum_{n=0}^{+\infty} a_n e_n = \lim_n \sum_{i=1}^{n} a_i e_i$, where the convergence is understood with respect to the topology of E. In this case we have $a_n = \langle e_n^*, x\rangle$ for all $n \in \mathbb{N}$. If E is a topological vector space with a topological basis (e_n), we have $a + P_n(x - a) \longrightarrow x$, for all $a, x \in E$. In this case, every continuous function is finitely determined by (e_n, e_n^*) and we prove in Corollary 3.2 , that the existence of partial derivatives (in the directions (e_n), when it is a Schauder basis) coincides with Gateaux differentiability for convex continuous functions. For further information about convex functions, see Borwein & Vanderwerff (2010).

The space $(FD_b(E), \|.\|_\infty)$ (resp. $(C_b(E), \|.\|_\infty)$) denotes the set of all real-valued bounded finitely determined functions on E with respect to a given biorthogonal system (e_n, e_n^*) (resp. of all real-valued bounded continuous functions on E) equipped with the sup-norm. It is easy to see that $(FD_b(E), \|.\|_\infty)$ is a Banach algebra.

This paper is organized as follows. In Section 2, we prove that if E is a Banach space and $(e_n)_n$ is a Schauder basis, the property of finite determination coincides with continuity for real-valued convex functions. Nonetheless, outside the convex case there are a many finitely determined nowhere continuous functions, in particular we prove that $FD_b(E) \setminus C_b(E)$ is an open dense subset of $FD_b(E)$ (Theorem 2.1 and Theorem 2.2). On the other hand, if E is a separable Banach space without Schauder basis, then the norm of E is not finitely determined by any fundamental biorthogonal system (e_n, e_n^*) of E (Corollary 2.1). A characterization of Schauder basis in term of the equivalence between continuity and the notion of finitely determined for convex functions is given in Corollary 2.2. In Section 3, using the notion of inf-finitely determined functions, we give a necessary and sufficient condition for a convex function to have a minimum at some point (Theorem 3.1). In Section 4, we use this result to generalize the Karush-Kuhn-Tucker theorem. Finally, in Section 5, we give some examples.

Notation : Throughout this paper, E denotes a topological vector (or Banach) space, $(x_n) \subset E$ denotes a sequence in E and whenever E is a normed space, $B_E(x, \rho)$ denotes the open ball centered at x of radius ρ. E^* denotes the dual space of E and $\langle \cdot, \cdot \rangle$ the duality product. For a convex function f, $\partial f(x)$ denotes the convex subdifferential of f at the point x.

2 Finitely determined functions

In this section, we study some properties of inf-finitely determined and finitely determined functions in Banach spaces equipped or not with a Schauder basis.

2.1 Banach space with a Schauder basis

Recall that a Banach space $(E, \|.\|)$ with a Schauder basis is necessarily separable. In our proofs, we will use the following well known result.

Lemma 2.1 *Phelps (1993, Proposition 1.1.9) A sequence (e_n) of nonzero vectors of a Banach space E is a Schauder basis in $\overline{\text{span}}(e_n : \ n \in \mathbb{N})$ if and only if there is a positive constant K such that*

$$\left\| \sum_{k=0}^{m} a_k e_k \right\| \leq K \left\| \sum_{k=0}^{n} a_k e_k \right\|$$

for every sequence of scalars (a_k) and all integers $m, \ n$ such that $m \leq n$.

Remarque D.1. In the context of this paper, Lemma 2.1 can be reformulated as follows : A sequence $(e_n) \subset E$ is a Schauder basis if and only if the linear operators (P_n) are uniformly bounded, i.e. there exists some $K > 0$ such that $\|P_n\| < K$ for all $n \in \mathbb{N}$.

The following is the main theorem of this subsection :

Theorem 2.1 *Let E be a Banach space equipped with a fundamental biorthogonal system (e_n, e_n^*) such that (e_n) is a Schauder basis. Then, for every real-valued convex function, the notions of finitely determined by (e_n, e_n^*) and classical continuity coincides.*

Before proceeding with the proof of Theorem 2.1, we recall simple facts about convex functions : every convex function $f : Y \to \mathbb{R}$ defined on a finite dimensional Banach space Y is continuous and every real-valued convex function $F : E \to \mathbb{R}$ defined on a Banach space E is continuous iff F is lower semicontinuous (lsc from now on) iff it is locally bounded from above at each point $x \in E$. Moreover, the last property is equivalent to be locally bounded from above at just one point $x \in E$. Also, we need the following lemma (see Aliprantis & Border (2006, Theorem 5.43, p. 188)).

Lemma 2.2 *Let $f : E \to \mathbb{R}$ be a convex function and $Y, \ Z$ be two closed subspaces of E such that $E = Y + Z$ and $Y \cap Z = 0$. Let $x_0 = y_0 + z_0 \in E$, where $y_0 \in Y$ and $z_0 \in Z$ fixed. Let $g : Y \to \mathbb{R}$, $h : Z \to \mathbb{R}$ be the convex functions defined by $g(y) = f(y + z_0)$ and $h(z) = f(y_0 + z)$. Then f is continuous if and only if both g and h are continuous.*

Démonstration. The necessity is straightforward. To prove the sufficiency, we show that f is locally bounded. Let $\overline{x} = \overline{y} + \overline{z} \in E$ where $\overline{y} \in Y$ and $\overline{z} \in Z$. Let $\epsilon > 0$, $u \in B_Y(\overline{y}, \epsilon)$ and $v \in B_Z(\overline{z}, \epsilon)$, then :

$$\begin{aligned} f(u+v) &= f\left(u - \frac{y_0}{2} + \frac{z_0}{2} + v - \frac{z_0}{2} + \frac{y_0}{2}\right) \\ &\leq \frac{1}{2}f(2u - y_0 + z_0) + \frac{1}{2}f(2v - z_0 + y_0) \\ &= \frac{1}{2}g(2u - y_0) + \frac{1}{2}h(2v - z_0). \end{aligned}$$

Since g and h are continuous, then f is locally bounded. □

We also highlight the limit which satisfies a finitely determined function f with respect to the point $a = 0$, i.e. if f is finitely determined at 0, it holds :

$$f(x) = \lim_n f(P_n(x)) \text{ for all } x \in E. \tag{2.1}$$

Proof of Theorem 2.1. Let $f : E \to \mathbb{R}$ be a continuous function. Since $(e_n)_n$ is a Schauder basis of E, f is finitely determined. Indeed, for every $a \in E$ and $x \in E$, the sequence $(a + P_n(x-a))_n$ converges to x. On the other hand, let us assume by contradiction that there exists a finitely determined convex function $f : E \to \mathbb{R}$ which is discontinuous. The idea of the proof is to find a point $\overline{x} \in E$ (by induction) such that $f(\overline{x})$ must take the value $+\infty$. Since f is convex and its domain is E, it must not be locally bounded from above at any point, in particular at 0. Let $x_1 \in E$ such that $\|x_1\| < 1$ and $f(x_1) > 1$. By equation (2.1), we get $N_1 \in \mathbb{N}$ such that $f(P_{N_1}(x)) > 1$. Let us call $\overline{x}_1 = P_{N_1}(x_1)$. In order to use Lemma 2.2, consider the subspaces $Y_1 := \text{span}(e_n : \ n \leq N_1)$ and $Z_1 := \overline{\text{span}}(e_n : \ n > N_1)$ and the point $\overline{x}_1 = \overline{x}_1 + 0$. Since f is discontinuous and Y_1 is a finite dimensional space, then the function $g_1 : Z_1 \to \mathbb{R}$ defined by $g_1(z) := f(\overline{x}_1 + z)$ is also discontinuous and satisfies equation (2.1). Inductively, suppose that we have constructed the vectors $\{\overline{x}_i\}_{i=1}^k$ and the increasing finite sequence $\{N_i\}_{i=1}^k$, where $\overline{x}_i \in \text{span}(e_n : n \in \ \{N_{i-1}+1, ..., N_i\})$, $N_0 = -1$, $g_{i-1}(\overline{x}_i) > i$ and $\|\overline{x}_i\| \leq \|P_{N_i}\|/2^{i-1}$. Let us define $Z_k = \overline{\text{span}}(e_n : \ n > N_k)$. By Lemma 2.2, the convex function $g_k : Z_k \to \mathbb{R}$ defined by $g_k(z) = f(\sum_{i=1}^k \overline{x}_i + z)$ is discontinuous and equation (2.1) is still valid for it. Since g_k is not locally bounded from above at 0, there exists $x_{k+1} \in Z_k$ such that $\|x_{k+1}\| \leq 1/2^k$ and $g_k(x_{k+1}) > k+1$. But using equation (2.1), we get an integer $N_{k+1} > N_k$ such that the vector $\overline{x}_{k+1} = P_{N_{k+1}}(x_{k+1})$ also satisfies $g_k(\overline{x}_{k+1}) > k+1$. Having constructed a sequence $(\overline{x}_n) \subset E$ using the previous induction, we can check that the function f at the point :

$$\overline{x} = \sum_{i=1}^{\infty} \overline{x}_i,$$

must take the value $+\infty$. In fact, to show that the point $\overline{x}$ is well-defined, we just use Lemma 2.1 to recall that the norm of the projections $(P_n)_n$ are uniformly bounded and compute :

$$\sum_{k=1}^{\infty} \|\overline{x}_k\| = \sum_{k=1}^{\infty} \|P_{N_k}(x_k)\| \leq \sum_{k=1}^{\infty} \frac{\sup_k\{\|P_k\|\}}{2^k} < \infty.$$

Finally, using equation (2.1) we deduce that :

$$f(\bar{x}) = \lim_k f(P_k(\bar{x})) = \lim_k f(P_{N_k}(\bar{x})) = \lim_k g_k(\overline{x}_{k+1}) = \infty,$$

which leads to a contradiction. Hence, we proved that, for real-valued convex functions, the notions of finitely determined and classical continuity coincide. □

Theorem 2.2 *In the following theorem, we prove that outside the convex case there are lots of finitely determined nowhere continuous functions. Under the hypothesis of Theorem 2.1, there exists a G_δ dense subset G of E such that for every $f \in C_b(E)$ and every $\varepsilon > 0$, there exists $\tilde{f}_\varepsilon \in FD_b(E)$ nowhere continuous on $E \setminus f^{-1}(0)$ such that $\|\tilde{f}_\varepsilon - f\|_\infty < \varepsilon$ and $\tilde{f}_\varepsilon = f$ on $f^{-1}(0) \cup G$. In particular, $C_b(E)$ is a closed subspace of $(FD_b(E), \|.\|_\infty)$ with empty interior.*

Démonstration. Let us define the following function :

$$\sigma(t) = \begin{cases} 1 \text{ if } t \in \mathbb{Q} \\ 0 \text{ if } t \in \mathbb{R} \setminus \mathbb{Q} \end{cases}$$

Let $\varepsilon > 0$ and $f \in C_b(E) \setminus \{0\}$. Let us set

$$\tilde{f}_\varepsilon(x) = \left(1 - \frac{\varepsilon\sigma(\langle e_0^*, x\rangle)}{\|f\|_\infty}\right) f(x) \text{ for all } x \in E.$$

Then, we have that for all $x \in E$

$$\begin{aligned} |\tilde{f}_\varepsilon(x) - f(x)| &= \frac{\varepsilon\sigma(\langle e_0^*, x\rangle)}{\|f\|_\infty}|f(x)| \\ &\leq \varepsilon. \end{aligned}$$

It follows that $\|\tilde{f}_\varepsilon - f\|_\infty \leq \varepsilon$ and $\tilde{f}_\varepsilon = f$ on $f^{-1}(0) \cup (e_0^*)^{-1}(\mathbb{R} \setminus \mathbb{Q})$. Let us set $\mathbb{R} = \cup_{n\in\mathbb{N}}\{q_n\}$, we have

$$G := (e_0^*)^{-1}(\mathbb{R} \setminus \mathbb{Q}) = \cap_{n\in\mathbb{N}}(e_0^*)^{-1}(\mathbb{R} \setminus \{q_n\}).$$

For each $n \in \mathbb{N}$, the set $(e_0^*)^{-1}(\mathbb{R} \setminus \{q_n\})$ is an open dense subset of E (in fact the complement of an affine subspace). Thus, G is a G_δ dense subset of E and $\tilde{f}_\varepsilon = f$ on $f^{-1}(0) \cup G$. To see that $\tilde{f}_\varepsilon \in FD_b(E)$, it suffices to show that the function $\tilde{\sigma} : x \mapsto \sigma(\langle e_0^*, x\rangle)$ belongs to $FD_b(E)$, since $FD_b(E)$ is a Banach algebra and $C_b(E) \subset FD_b(E)$. Indeed, for all $a, x \in E$, we have $\tilde{\sigma}(a + P_k(x - a)) = \tilde{\sigma}(x)$. Thus, $\tilde{\sigma} \in FD_b(E)$ and so we have $\tilde{f}_\varepsilon \in FD_b(E)$. Now, we prove that $\tilde{f}_\varepsilon$ is nowhere continuous on $E \setminus f^{-1}(0)$. Indeed, let $x \in E$ and $a \in E \setminus f^{-1}(0)$,

$$\begin{aligned} |\tilde{f}_\varepsilon(x) - \tilde{f}_\varepsilon(a)| &= |(1 - \frac{\varepsilon\sigma(\langle e_0^*, x\rangle)}{\|f\|_\infty})(f(x) - f(a)) + \\ &\quad \frac{\varepsilon(\sigma(\langle e_0^*, a\rangle) - \sigma(\langle e_0^*, x\rangle))}{\|f\|_\infty} f(a)| \\ &\geq |\frac{\varepsilon(\sigma(\langle e_0^*, a\rangle) - \sigma(\langle e_0^*, x\rangle))}{\|f\|_\infty} f(a)| - \\ &\quad |1 - \frac{\varepsilon\sigma(\langle e_0^*, x\rangle)}{\|f\|_\infty}||f(x) - f(a)| \end{aligned} \tag{2.2}$$

Case 1 : if $\langle e_0^*, a\rangle \in \mathbb{R} \setminus \mathbb{Q}$, we choose rational numbers $r_k(a) \in \mathbb{Q}$ such that $|r_k(a) - \langle e_0^*, a\rangle| \leq 2^{-k}$ for all $k \in \mathbb{N}$, and we set $x_k = a + (r_k(a) - \langle e_0^*, a\rangle)e_0$ for all $k \in \mathbb{N}$. Then, $\|x_k - a\| \leq 2^{-k}$ for all $k \in \mathbb{N}$ and $|\sigma(\langle e_0^*, a\rangle) - \sigma(\langle e_0^*, x_k\rangle)| = 1$. It follows from (2.2) that

$$|\tilde{f}_\varepsilon(x_k) - \tilde{f}_\varepsilon(a)| \geq \frac{\varepsilon|f(a)|}{\|f\|_\infty} - |1 - \frac{\varepsilon\sigma(\langle e_0^*, x_k\rangle)}{\|f\|_\infty}||f(x_k) - f(a)|.$$

Since f is continuous, sending k to $+\infty$, we have that

$$\liminf_k |\tilde{f}_\varepsilon(x_k) - \tilde{f}_\varepsilon(a)| \geq \frac{\varepsilon|f(a)|}{\|f\|_\infty} > 0,$$

which implies that $\tilde{f}_\varepsilon$ is not continuous at a.

Case 2 : in a similar way, if $\langle e_0^*, a\rangle \in \mathbb{Q}$, we choose irrational numbers $r_k(a) \in \mathbb{R}\setminus\mathbb{Q}$ such that $|r_k(a) - \langle e_0^*, a\rangle| \leq 2^{-k}$ for all $k \in \mathbb{N}$, and we put $x_k = a + (r_k(a) - \langle e_0^*, a\rangle)e_0$ for all $k \in \mathbb{N}$. Then, $\|x_k - a\| \leq 2^{-k}$ for all $k \in \mathbb{N}$ and $|\sigma(\langle e_0^*, a\rangle) - \sigma(\langle e_0^*, x_k\rangle)| = 1$. Then, using (2.2) and sending k to $+\infty$, we have that

$$\liminf_k |\tilde{f}_\varepsilon(x_k) - \tilde{f}_\varepsilon(a)| \geq \frac{\varepsilon|f(a)|}{\|f\|_\infty} > 0,$$

which implies also that $\tilde{f}_\varepsilon$ is not continuous at a.

Finally, we proved that for every $f \in C_b(E)\setminus\{0\}$ and every $\varepsilon > 0$, there exists $\tilde{f}_\varepsilon \in FD_b(E)$ nowhere continuous on $E\setminus f^{-1}\{0\}$ such that $\|\tilde{f}_\varepsilon - f\|_\infty \leq \varepsilon$ and $\tilde{f}_\varepsilon = f$ on $f^{-1}\{0\}\cup G$ (the case of $f = 0$ is also clear). Since $C_b(E)$ is a closed subset of $FD_b(E)$, it is now clear that $FD_b(E)\setminus C_b(E)$ is an open and dense subset of $FD_b(E)$. This concludes the proof. □

2.2 Topological vector space without Schauder basis

In the following proposition, it is shown that a convex norm-continuous function is not necessarily finitely determined by a biorthogonal system if the sequence is not a Schauder basis. Note that, finding a separable Banach space without a Schauder basis is non-trivial result due to Enflo (1973).

Proposition 2.1 *Let E be a separable Banach space. Then for every fundamental biorthogonal system (e_n, e_n^*) such that (e_n) is not a Schauder basis, there exists a continuous linear form $y^* \in E^*$ which is not finitely determined by (e_n, e_n^*).*

Démonstration. First, since the function $\phi_n : E^* \to \mathbb{R}$ defined by $\phi_n(x^*) := \|x^* \circ P_n\|$ is convex continuous for each $n \in \mathbb{N}$, the function $\Phi : E^* \to \mathbb{R}\cup\{+\infty\}$ defined by $\Phi(x^*) := \sup_n \phi_n$ is lsc and convex. We prove that there exists $x^* \in E^*$ such that $\Phi(x^*) = +\infty$. Indeed, by Lemma 2.1 we already know that $\sup_n \|P_n\| = +\infty$, with which we can compute the following estimation :

$$\begin{aligned} +\infty = \sup_n \|P_n\| &= \sup_n \sup_{\|x\|=1} \|P_n x\| = \sup_n \sup_{\|x\|=1} \sup_{\|x^*\|=1} |\langle x^*, P_n x\rangle| \\ &= \sup_n \sup_{\|x^*\|=1} \sup_{\|x\|=1} |\langle x^* \circ P_n, x\rangle| \leq \sup_n \sup_{\|x^*\|=1} \|x^* \circ P_n\| = \sup_{\|x^*\|=1} \Phi(x^*), \end{aligned}$$

thus, we can deduce that the function Φ is not locally bounded at 0, then it is not continuous. Since Φ is lsc (and for real-valued convex functions, lsc and continuity are equivalent in Banach spaces), there exists some $\overline{x}^* \in E^*$ such that $\Phi(\overline{x}^*) = +\infty$. Hence, $\overline{x}^*$ is not finitely determined by (e_n, e_n^*), otherwise, from equation (2.1) and Banach-Steinhaus Theorem we have that $\Phi(\overline{x}^*) \in \mathbb{R}$, which is a contradiction. □

Remark 2.1 Since Φ is a convex lsc function, in the proof of Proposition 2.1 we have proven that its domain has empty interior.

Corollary 2.1 *By f^* we denote the Fenchel conjugate of a function f : for all $x^* \in E^*$*

$$f^*(x^*) := \sup_{x \in E}\{\langle x^*, x\rangle - f(x)\}.$$

Let E be a separable Banach space and let $(e_n, e_n^*)_n$ be a fundamental biorthogonal system of E such that (e_n) is not a Schauder basis. Then, there is no finitely determined (by (e_n, e_n^*)) convex continuous function $f : E \to \mathbb{R}$ such that $\text{int}(\text{dom}(f^*)) \neq \emptyset$. In particular, the norm $\|\cdot\|$ of E is not finitely determined.

Démonstration. Let $f : E \to \mathbb{R}$ be a convex function such that the domain of its Fenchel conjugate f^* has nonempty interior. Let $x^* \in \text{int}(\text{dom}(f^*))$. Since f^* is convex and lsc, it is bounded from above at x^*. Then there exists some $\rho > 0$ and $M > 0$ such that $f^*(y^*) \leq M$ for all $y^* \in B_{E^*}(x^*, \rho)$. By definition of f^*, we have :

$$\langle y^*, x\rangle \leq f^*(y^*) + f(x) \leq M + f(x),\ \forall x \in E,\ \forall y^* \in B_{E^*}(x^*, \rho). \tag{2.3}$$

Let $\Phi : E^* \to \mathbb{R} \cup \{+\infty\}$ be the function defined in the proof of Proposition 2.1. We know that its domain has empty interior, thus there exists a $\overline{y}^* \in B_{E^*}(x^*, \rho)$ such that $\Phi(\overline{y}^*) = +\infty$. By Banach-Steinhaus Theorem, there exists $x \in X$ such that the sequence $(\overline{y}^* \circ P_n(x))$ is not bounded from above. Hence, by equation (2.3) we have that equation (2.1) is not satisfied at the point x. Finally, since the Fenchel conjugate of the norm is the function $f : E^* \to \mathbb{R} \cup \{\infty\}$ such that $f(y^*) = 0$ if $\|y^*\| \leq 1$ and $+\infty$ otherwise, we conclude the theorem. □

The notion of finitely determined function, applied to convex functions, characterizes the Banach spaces with a Schauder basis.

Corollary 2.2 *Let E be a separable Banach space and let $(e_n, e_n^*)_n$ be a fundamental biorthogonal system of E. Then, (e_n) is a Schauder basis if and only if the notions of finitely determined by (e_n, e_n^*) and norm continuity coincide for real-valued convex functions.*

Démonstration. The proof is a consequence of Theorem 2.1 and Corollary 2.1. □

We give below a useful example of inf-finitely determined (with respect to some points) convex function having directional derivative but which is nowhere Gateaux differentiable. We need the following definition.

Definition 2.1 (*Directional-differentiability*) Let E be a Banach space and let $(e_n, e_n^*)_n$ be a biorthogonal system of E. We say that f is differentiable at a in the directions (e_n) if the following limit exists for all $n \in \mathbb{N}$

$$f'(a; e_n) := \lim_{\substack{t \to 0 \\ t \neq 0}} \frac{1}{t}\Big(f(a + te_n) - f(a)\Big).$$

Example 2.1 Let $E = l^\infty(\mathbb{N})$ the Banach space of bounded sequences. We denote $e_n := (\delta_j^n)$ the elements of $l^\infty(\mathbb{N})$ where δ_j^n is the Kronecker symbol satisfying $\delta_j^n = 1$ if $j = n$ and 0 if $j \neq n$. Let (e_n, e_n^*) be the natural biorthogonal system of $l^\infty(\mathbb{N})$. Let $p : l^\infty(\mathbb{N}) \longrightarrow \mathbb{R}$ be the function defined for all $x = (x_n) \in l^\infty(\mathbb{N})$ by

$$p(x) = \limsup |x_n|.$$

Then,

(1) p is a continuous seminorm ($p(x) \leq \|x\|_\infty$ for all $x \in l^\infty(\mathbb{N})$), is differentiable in the directions $(e_n)_{n\geq 0}$ at each $x \in l^\infty(\mathbb{N})$ and we have $p'(x; e_n) = 0$ for all $n \in \mathbb{N}$ and all $x \in l^\infty(\mathbb{N})$. However, p is nowhere Gateaux differentiable.

(2) p is inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to a if and only if $p(a) = 0$ (i.e. $a \in c_0(\mathbb{N})$).

Démonstration. It is well-known that p is a continuous seminorm (with respect the norm $\|.\|_\infty$), nowhere Gateaux differentiable (see Phelps (1993, Example 1.21)). We show that p is differentiable at each x in the directions (e_n). Indeed, for each fixed integer $n \in \mathbb{N}$ and each $t \in \mathbb{R}$, it is easy to see that $p(x + te_n) = p(x)$. It follows that $p'(x; e_n) = 0$ for all $n \in \mathbb{N}$ and all $x \in l^\infty(\mathbb{N})$. On the other hand, p is inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to each element a satisfying $p(a) = 0$. Indeed, it is clear that $p(a + P_k(x - a)) = p(a)$ for all $a, x \in l^\infty(\mathbb{N})$. So, if $p(a) = 0$, then we have that $p(a + P_k(x - a)) = 0 \leq p(x)$ for all $x \in l^\infty(\mathbb{N})$. Thus, $\inf_{k\in\mathbb{N}} p(a + P_k(x - a)) \leq p(x)$, for all $x \in l^\infty(\mathbb{N})$. If $p(a) \neq 0$, then $p(a + P_k(0 - a)) = p(a) > 0 = p(0)$ and so in this case p is not inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to a. □

Note that in the Banach space $(l^\infty(\mathbb{N}), \|.\|_\infty)$ the sequence $e_n := (\delta_j^n)$ (where δ_j^n is the Kronecker symbol), is not a topological basis since in general $\|P_k(x) - x\|_\infty$ does not converge to 0, when $k \longrightarrow +\infty$.

Proposition 2.2 *Let $f : (l^\infty(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$ be a L-Lipschitz continuous function ($L \geq 0$) and $p(x) = \limsup_k |x_k|$. Then, $f + Lp$ is inf-finitely determined with respect to each point a of $c_0(\mathbb{N})$.*

Démonstration. Since f is L-Lipschitz continuous, we have that for all $x \in l^\infty(\mathbb{N})$

$$\begin{aligned} |f(a + P_k(x - a)) - f(x)| &\leq L\|a + P_k(x - a) - x\|_\infty \\ &= L \sup_{n\geq k+1} |a_n - x_n| \\ &\leq L \sup_{n\geq k+1} |a_n| + L \sup_{n\geq k+1} |x_n| \end{aligned}$$

Besides, we have that $p(a+P_k(x-a)) = p(a) = 0$ since $a \in c_0(\mathbb{N})$. Thus, using the above inequality we get

$$f(a + P_k(x - a)) + Lp(a + P_k(x - a)) \leq f(x) + L \sup_{n\geq k+1} |a_n| + L \sup_{n\geq k+1} |x_n|.$$

Taking the limit superior over $k \in \mathbb{N}$, we get that

$$\limsup_{k\longrightarrow+\infty} (f(a + P_k(x - a)) + Lp(a + P_k(x - a))) \leq f(x) + Lp(x).$$

and so,

$$\inf_{k\in\mathbb{N}} (f(a + P_k(x - a)) + Lp(a + P_k(x - a))) \leq f(x) + Lp(x).$$

Hence, f is inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to $a \in c_0(\mathbb{N})$. □

3 Necessary and Sufficient Condition of Convex Optimality

Note that we can construct on $l^\infty(\mathbb{N})$ canonical examples of convex inf-finitely determined functions at some point $a \in l^\infty(\mathbb{N})$ (and norm continuous)

$$f : (l^\infty(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$$

which are differentiable at a in the directions of the canonical basis $(e_n)_{n\geq 0}$ of $c_0(\mathbb{N})$ but are not Gateaux differentiable at this point. We proceed as follows : let $g : (c_0(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$ be a convex L-Lipschitz continuous function which is Gateaux differentiable but not Fréchet-differentiable at $a \in c_0(\mathbb{N})$ (such function g always exists and can be constructed canonically, see for instance Bachir (2017)). Let us define $f : (l^\infty(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$ by

$$f(x) := \inf_{y \in c_0(\mathbb{N})} \{g(y) + L(\|x-y\|_\infty + p(x-y))\},$$

where $p(x) = \limsup_n |x_n|$ for all $x \in l^\infty(\mathbb{N})$. The function f is convex and Lipschitz continuous satisfying $f_{|c_0(\mathbb{N})} = g$, where $f_{|c_0(\mathbb{N})}$ denotes the restriction of f to $c_0(\mathbb{N})$. It follows that $f'(a, ; e_n) = g'(a; e_n)$ exists for all $n \in \mathbb{N}$. However, f cannot be Gateaux differentiable at $a \in c_0(\mathbb{N})$, otherwise $f_{|c_0(\mathbb{N})} = g$ would be Fréchet-differentiable at a since the canonical embedding $i : c_0(\mathbb{N}) \longrightarrow l^\infty(\mathbb{N})$ is a limited operator (see Bachir (2017, Corollary 1) for details). Note also that f is inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to each point of $a \in c_0(\mathbb{N})$.

Thus, in infinite dimension, the fact that a convex continuous function f is differentiable at a in the directions (e_n) does not implies that f is Gateaux differentiable at a (see also Example 2.1).

Definition 3.1 (*Qualification condition*) Let E be a topological vector space equipped with a biorthogonal system (e_n, e_n^*) (not necessarily a topological basis). Let $X \subset E$ be a non-empty subset of E and let $a \in X$ be a fixed point of E. We say that the set X is qualified at a if the following conditions hold.

For all $n \in \mathbb{N}$, there exists $\alpha_n > 0$ such that $a + te_n \in X$ for all $|t| < \alpha_n$.

$P_k(X - a) \subset X - a$ for all $k \in \mathbb{N}$.

We define the space E_k as the image of E by P_k, that is, $E_k = P_k(E)$, which is a finite dimensional vector space isomorphic to $\mathbb{R}^k$. Let X be a subset of E. For all $k \in \mathbb{N}$, we denote $X_k := P_k(X)$ and by $Int_{E_k}(X_k)$ we mean the relative interior of X_k, that is the interior of X_k in $E_k \simeq \mathbb{R}^k$.

Remark 3.1 Provided that X is a convex set, the qualification condition implies that $P_k(a) \in Int_{E_k}(X_k)$ for all $k \in \mathbb{N}$, but is in general weaker than the fact that $a \in Int_E(X)$. Indeed, let $E := (l^1(\mathbb{N}), \|.\|_1)$ and let $X_+ := \{(x_n) \subset l^1(\mathbb{N}) : x_n > 0; \forall n \in \mathbb{N}\}$ be the convex positive cone of $l^1(\mathbb{N})$. Then,

$Int(X_+) = \emptyset$,

however, X_+ is qualified at each of its points.

We give below the main result of this section which gives a necessary and sufficient condition of optimality by using the notion of inf-finitely determined function. The proof is based on a reduction to the finite dimension. For recent works on convex optimization in finite dimension, we refer for instance to Lu et al. (2018) and Taylor et al. (2017).

Theorem 3.1 *Let E be a topological vector space equipped with a biorthogonal system* (e_n, e_n^*)

(not necessarily a topological basis). Let $X \subset E$ be a non-empty convex subset of E and let $a \in X$. Suppose that X is qualified at a. Let $f : X \longrightarrow \mathbb{R}$ be a convex function, such that f is inf-finitely determined on X with respect to a and differentiable at a in the directions (e_n). Then, the following assertions are equivalent.

(a) $f(a) = \inf_{x \in X} f(x)$

(b) $f'(a, e_n) = 0, \ \ \forall n \in \mathbb{N}$

Démonstration. The part $(a) \Longrightarrow (b)$ is easy. Indeed, suppose that $f(a) = \inf_{x \in X} f(x)$. Then, we have that

$$0 \leq f(x) - f(a) \ \ \forall x \in X.$$

In particular, since X is qualified at a, for all $n \in \mathbb{N}$ there exists $\alpha_n > 0$ such that for all $|t| < \alpha_n$, we have that $a + te_n \in X$ and so

$$0 \leq f(a + te_n) - f(a).$$

Thus, we get that $0 \leq \lim_{t \longrightarrow 0^+} \frac{f(a+te_n)-f(a)}{t} = f'(a; e_n)$. Similarly, we have $0 \geq \lim_{t \longrightarrow 0^-} \frac{f(a+te_n)-f(a)}{t} = f'(a; e_n)$. Hence, $f'(a, e_n) = 0, \ \ \forall n \in \mathbb{N}$.

Now, we prove $(b) \Longrightarrow (a)$. Let us define $f_k : X_k \subset E_k \longrightarrow \mathbb{R}$ as follows : for all $x \in X$,

$$f_k(P_k(x)) := f(a + P_k(x - a)).$$

Note that f_k is well-defined and that $P_k(a) \in Int_{E_k}(X_k)$ for all $k \in \mathbb{N}$ (by the qualification condition of X at a, see Remark 3.1). We prove that, for all $k \in \mathbb{N}$, the convex function f_k is Fréchet-differentiable at $P_k(a)$. Indeed, for all $n \leq k$ we have that $P_k(e_n) = e_n$ and we have that $f_k(P_k(a)) = f(a)$. Thus, for all $n \leq k$ and all small t we have

$$\begin{aligned} f_k(P_k(a) + te_n) - f_k(P_k(a)) &= f_k(P_k(a + te_n)) - f_k(P_k(a)) \\ &= f(a + te_n) - f(a). \end{aligned} \tag{3.1}$$

It follows that

$$f'_k(P_k(a); e_n) \quad = \quad f'(a; e_n). \tag{3.2}$$

This shows that $f'_k(P_k(a); e_n)$ exists for each $e_n \in E_k$, $n \in \{0, ..., k\}$. Since f_k is a convex function on the convex set X_k, $P_k(a) \in Int_{E_k}(X_k)$ and since E_k is of finite dimension with $(e_n)_{0 \leq n \leq k}$ as a basis, then it is well known (see Kadets (1997, Theorem 6.1.1)) that f_k is Fréchet-differentiable at $P_k(a)$.

Thanks to the equations (b) and (3.2), we have that for all $k \in \mathbb{N}$,

$$Df_k(P_k(a)) = 0, \tag{3.3}$$

where $Df_k(P_k(a))$ denotes the Fréchet-derivative of f_k at $P_k(a)$. Moreover, f_k is a convex function defined on the convex set $X_k \subset E_k$ and $P_k(a) \in Int_{E_k}(X_k)$ (by the qualification condition). It follows that

$$f_k(P_k(a)) = \inf_{y \in X_k} f_k(y). \tag{3.4}$$

For all $x \in X$ and all $k \in \mathbb{N}$, we have that $P_k(x) \in X_k$, then by using (3.4) we get

$$f(a) = f_k(P_k(a)) = \inf_{y \in X_k} f_k(y) \leq f_k(P_k(x)) := f(a + P_k(x - a)).$$

Since f is inf-finitely determined on X with respect to the point a, then by taking the infimum in the above inequality we obtain that for all $x \in X$

$$f(a) \leq \inf_{k \in \mathbb{N}} f(a + P_k(x - a)) \leq f(x).$$

It follows that $f(a) = \inf_{x \in X} f(x)$. □

Remark 3.2 The example of the (norm) continuous seminorm $p : l^\infty(\mathbb{N}) \longrightarrow \mathbb{R}$, $x \mapsto \limsup_n |x_n|$ shows that the condition of inf-finitely determined property cannot be dropped from the hypothesis of Theorem 3.1. Indeed, we know that for each $a \in l^\infty(\mathbb{N})$, we have that $p'(a, e_n) = 0$ for all $n \in \mathbb{N}$ (see Example 2.1). On the other hand, if $p(a) \neq 0$, then clearly a is not a minimum for p. Thus, Theorem 3.1 does not apply for p at a if $p(a) \neq 0$. This is due to the fact that p is not inf-finitely determined on $l^\infty(\mathbb{N})$ with respect to a if $p(a) \neq 0$. However, if $p(a) = 0$, then p is inf-finitely determined on $l^\infty(\mathbb{N})$ with respect a. In this case Theorem 3.1 applies and p has a minimum at a (which is trivial here since $p(a) = 0 \leq p(x)$ for all $a \in c_0(\mathbb{N})$ and all $x \in l^\infty(\mathbb{N})$).

The above Theorem shows that, for a convex function which is inf-finitely determined with respect to $a \in E$ and differentiable at a in the directions $(e_n)_{n \geq 0}$, a necessary and sufficient condition to have a minimum at a is to satisfy $f'(a, e_n) = 0, \ \forall n \in \mathbb{N}$. In several examples, it is easy to calculate the derivative $f'(a, e_n)$ and also to solve $f'(a, e_n) = 0, \ \forall n \in \mathbb{N}$. Thus, the candidate for the minimum can be exhibited. Since the condition is also sufficient, we get the points that realizes the minimum (see Section 5 for examples). Moreover, in infinite dimension, the differentiability of f in the directions (e_n) at some point a, does not imply in general its Gateaux differentiable at a. An example in the space $l^\infty(\mathbb{N})$ illustrating this situation was given in Example 2.1. Thus, Theorem 3.1 can be applied for instance in $E = l^\infty(\mathbb{N})$ without the Gateaux differentiability assumption. For example, combining Proposition 2.2 and Theorem 3.1, we get the following corollary :

Corollary 3.1 *Let $f : (l^\infty(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$ be a convex L-Lipschitz continuous function ($L \geq 0$) and $p(x) = \limsup_k |x_k|$. Suppose that there exists $a \in c_0(\mathbb{N})$ such that $f'(a, e_n) = 0$ for all $n \in \mathbb{N}$. Then, $f + Lp$ has a minimum on $l^\infty(\mathbb{N})$ at a.*

However, in Hausdorff locally convex topological vector spaces equipped with a biorthogonal system (e_n, e_n^*), where (e_n) is a topological basis, the situation is different. Indeed, as we show it in Corollary 3.2, in this situation, the differentiability of a convex continuous function f in the directions (e_n) at some point a, is equivalent to the Gateaux differentiability of f at a. This result is a natural extension of a well-known result concerning the Gateaux differentiability of convex functions in finite dimension (see Kadets (1997, Theorem 6.1.1)). Note that this result applies even if E is not a normed space like the Fréchet space $(\mathbb{R}^\mathbb{N}, d_{\mathbb{R}^\mathbb{N}})$ of all real sequences, equipped with the distance : for all $x = (x_n)$ and $y = (y_n)$,

$$d_{\mathbb{R}^\mathbb{N}}(x, y) := \sum_{i=1}^{+\infty} \frac{2^{-i}|x_i - y_i|}{1 + |x_i - y_i|}$$

Corollary 3.2 *Let E be a Hausdorff locally convex topological vector space equipped with a biorthogonal system (e_n, e_n^*), where (e_n) is a topological basis. Let $f : E \longrightarrow \mathbb{R} \cup \{+\infty\}$ be a convex function. Suppose that f is finite and upper semicontinuous at $a \in E$ and that $f'(a; e_n)$ exists for all $n \in \mathbb{N}$ with $\partial f(a) \neq \emptyset$. Then, $\partial f(a)$ is a singleton. In consequence, if f is convex and continuous at a, then $f'(a; e_n)$ exists for all $n \in \mathbb{N}$, if and only if f is Gateaux differentiable at a.*

Démonstration. Suppose that $f'(a; e_n)$ exists for all $n \in \mathbb{N}$ and let $p, q \in \partial f(a)$. Then, a is a minimum of the functions $f - p$ and $f - q$. On the other hand, clearly E is qualified at a and the functions $f - p$ and $f - q$ are inf-finitely determined on E with respect to a since they are upper semicontinuous at this point. Thus, applying Theorem 3.1, once to $f - p$ and again to $f - q$, we obtain that $\langle p, e_n \rangle = f'(a, e_n) = \langle q, e_n \rangle, \ \forall n \in \mathbb{N}$. It follows that $p = q$ since $p, q \in E^*$ and $(e_n)_{n \geq 0}$ is a topological basis. Thus, $\partial f(a)$ is a singleton. If in addition f is convex continuous at a then we know from Moreau (1966, Proposition 10.c, p.60,) that $\partial f(a) \neq \emptyset$. It follows that $\partial f(a)$ is a singleton. To conclude, we know from Moreau (1966, Corollary 10.g, p. 66) that f is Gateaux differentiable at a if and only if $\partial f(a)$ is a singleton. □

It is well known (see for instance Phelps (1993, Examples 1.4)) that the norm of $l^1(\mathbb{N})$, $\|x\|_1 = \sum_{n \geq 0} |x_n|$ is Gateaux differentiable at $x = (x_n)$ if and only if $x_n \neq 0$ for all $n \in \mathbb{N}$. This fact is a particular case of a more general result given in the following proposition, which is a consequence of Corollary 3.2. Indeed, it suffices to take $u_n(t) = |t|$ for all $t \in \mathbb{R}$ and all $n \in \mathbb{N}$ in the following proposition, to see more simply why, the norm $\|.\|_1$ is Gateaux differentiable at $x = (x_n)$ if and only if $x_n \neq 0$ for all $n \in \mathbb{N}$.

Proposition 3.1 *Let $(E, \|.\|)$ be a Banach space having a Schauder basis (e_n) and let (e_n, e_n^*) be a biorthogonal system. For each $n \in \mathbb{N}$, let $u_n : \mathbb{R} \longrightarrow \mathbb{R}$ be a convex continuous function. Suppose that the series $\sum_{n=0}^{+\infty} u_n(\langle e_n^*, \cdot \rangle)$ converges pointwise to a real valued continuous function f. Then,*

(i) f is Gateaux differentiable at $x \in E$, if and only if, for all $n \in \mathbb{N}$ the function u_n is differentiable at $\langle e_n^*, x \rangle$. In this case, we have that for all $h \in E$,

$$Df(x)(h) = \sum_{n=0}^{+\infty} \langle e_n^*, h \rangle u_n'(\langle e_n^*, x \rangle),$$

where $Df(x)$ denotes the Gateaux-derivative of f at x.

(ii) the set of points at which f is not Gateaux differentiable is a countable union of affine hyperplanes.

Démonstration. (i) It is clear that for each $n \in \mathbb{N}$, we have that $f'(x, e_n)$ exists if and only if u_n is differentiable at $\langle e_n^*, x \rangle$, in this case $f'(x, e_n) = u_n'(\langle e_n^*, x \rangle)$. Thus, we conclude using Corollary 3.2.

(ii) It is well known that a convex continuous function from $\mathbb{R}$ to $\mathbb{R}$ is differentiable at all but (at most) countably many points of $\mathbb{R}$ (see Phelps (1993, Theorem 1.16.)). Thus, for each $n \in \mathbb{N}$, the set

$$C_n := \{t \in \mathbb{R} : u_n'(t) \text{ does not exist } \},$$

is at most a countable subset of $\mathbb{R}$. Using part (i), we clearly see that f is not Gateaux differentiable at $x \in E$ if and only if $x \in \cup_{n \in \mathbb{N}} \cup_{t \in C_n} (e_n^*)^{-1}(\{t\})$. Finally, it is clear that $(e_n^*)^{-1}(\{t\})$ is an affine hyperplane for each $n \in \mathbb{N}$ and each $t \in C_n$. □

4 Application to the Karush-Kuhn-Tucker theorem

We follow the notation given in Barbu & Precupanu (2012). Let E be a real linear space and $f : E \longrightarrow \mathbb{R} \cup \{+\infty\}$ be a given function. Consider the minimizing problem for the function f on a subset $A_E \subset E$, that is, the problem

$$(\mathcal{P}) \qquad \min\{f(x) : x \in A_E\}.$$

The set A_E constitutes the constraints of Problem $(\mathcal{P})$. We say that an element $\bar{x} \in E$ is feasible if $\bar{x} \in A_E \cap \text{dom}(f)$. The mathematical programming problem $(\mathcal{P})$ is said to be consistent if $A_E \cap \text{dom}(f) \neq \emptyset$, that is, if it has feasible elements. A feasible element x_0 is called an optimal solution of $(\mathcal{P})$ if

$$f(x_0) = \inf\{f(x) : x \in A_E\}.$$

The subset A_E is often defined by the solutions of a finite number of inequalities as in

$$A_E := \{x \in E : g_i(x) \leq 0, \forall i = 1, ..., m\},$$

where g_i are extended real-valued functions on E. Let us set

$$E_0 := \text{dom}(f) \cap_{i=1}^{m} \text{dom}(g_i).$$

We call Slater's constraint qualification, the following condition :

(S) There exists a point $\bar{x} \in A_E$ such that $g_i(\bar{x}) < 0$, $\forall i = 1, 2, ..., m$.

In the following corollary, we give a Karush-Kuhn-Tucker theorem in infinite dimension, where Gateaux differentiability is replaced by the weaker condition of differentiability in the directions of (e_n).

Corollary 4.1 *(Karush-Kuhn-Tucker theorem in countable dimension) Let E be a topological vector space equipped with a biorthogonal system (e_n, e_n^*) (not necessarily a topological basis). Let $f, g_1, ..., g_m : E \longrightarrow \mathbb{R} \cup \{+\infty\}$ be convex functions. Suppose that E_0 is qualified at $x_0 \in A_E$ and that $f, g_1, ..., g_m$ are finitely determined functions on E_0 with respect to x_0 and differentiable at x_0 in the directions (e_n). Then, we have $(1) \Longrightarrow (2)$. If moreover, the Slater's condition (S) is satisfied, then $(1) \Longleftrightarrow (2)$.*

(1) *There exists $\lambda_i^* \geq 0$ for all $i \in \{1, ..., m\}$ such that*

$$\lambda_i^* g_i(x_0) = 0, \forall i \in \{1, 2, ..., m\} \tag{4.1}$$

$$f'(x_0, e_n) + \sum_{i=1}^{m} \lambda_i^* g_i'(a, e_n) = 0, \quad \forall n \in \mathbb{N}$$

(2) $f(x_0) = \inf\{f(x), x \in A_E\}$.

Démonstration. $(1) \Longrightarrow (2)$. We apply Theorem 3.1 to the function $\tilde{f} = f + \sum_{i=1}^{m} \lambda_i^* g_i$ which is finitely determined on E_0 with respect to x_0 and differentiable at x_0 in the directions (e_n) with

$\tilde{f}'(x_0; e_n) = 0$ for all $n \in \mathbb{N}$, to get that for all $x \in E_0$

$$f(x_0) + \sum_{i=1}^{m} \lambda_i^* g_i(x_0) \quad \leq \quad f(x) + \sum_{i=1}^{m} \lambda_i^* g_i(x).$$

Since, $\lambda_i^* g_i(x_0) = 0$ for all $i \in \{1, 2, ..., m\}$ by hypothesis, then for all $x \in A_E \cap E_0$, we obtain that

$$\begin{aligned} f(x_0) \quad &\leq \quad f(x) + \sum_{i=1}^{m} \lambda_i^* g_i(x) \\ &\leq \quad f(x) \quad (\text{Since } \forall x \in A_E : \lambda_i^* \geq 0; g_i(x) \leq 0). \end{aligned}$$

Hence, $f(x_0) = \inf\{f(x), x \in A_E \cap E_0\} = \inf\{f(x), x \in A_E\}$.

(2) $\Longrightarrow$ (1). If moreover (S) is satisfied, then the implication (2) $\Longrightarrow$ (1) follows easily from Barbu & Precupanu (2012, Theorem 3.4). □

Hereafter, we give a weaker version of the previous corollary intended for application by a wide audience (e.g. economists). It does not rely on the notions of finite determination, but still covers most practical applications. This corollary is presented on stackexchange.[51]

Corollary 4.2 *(Karush-Kuhn-Tucker theorem for series with convex continuous terms) Let $X \subset \mathbb{R}^{\mathbb{N}}$ be a nonempty convex subset of $\mathbb{R}^{\mathbb{N}}$ and let $x^* \in Int(X)$. Let $f, g_1, g_2, ..., g_m : X \to \mathbb{R}$ be convex functions continuous at x^* and term-to-term differentiable at x^*, i.e such that the functions $f_{n,x^*}(x_n) := f\left((x_1^*, ..., x_{n-1}^*, x_n, x_{n+1}^*, ...)\right)$ and $g_{j,n,x^*}(x_n) := g_j\left((x_1^*, ..., x_{n-1}^*, x_n, x_{n+1}^*, ...)\right)$ are differentiable at x_n for all $n \in \mathbb{N}$ and $j \in \{1, 2, ..., m\}$.*

(Qualification condition) Suppose that for all $k \in \mathbb{N}^*$ and for all $x \in X$, $x^* + P^k(x - x^*) = \left(x_1, ..., x_k, x_{k+1}^*, x_{k+2}^*, ...\right) \in X$. If there exist $\left(\lambda_j^*\right)_j \in (\mathbb{R}_+)^{\mathbb{N}}$ such that

$$\lambda_j^* g_j(x^*) = 0,\ \forall j \in \{1, 2, ..., m\} \tag{4.2}$$

$$f'_{n,x^*}(x_n^*) + \sum_{j=1}^{m} \lambda_j^* g'_{j,n,x^*}(x_n^*) = 0,\ \forall n \in \mathbb{N} \tag{4.3}$$

(Sufficiency) Then x^* is an optimal solution on $\Gamma := \{(x_i)_i \in X : g_1(x) \leq 0, ..., g_m(x) \leq 0\}$:

$$f(x^*) = \inf_{x \in \Gamma} f(x)$$

(Necessity) Besides, if x^* is an optimal solution on Γ and if the Slater condition $Int(\Gamma) \neq \emptyset$ is verified, then there exist unique $\left(\lambda_j^*\right)_j \in (\mathbb{R}_+)^{\mathbb{N}}$ which verify the (Karush-Kuhn-Tucker) conditions (4.2) and (4.3).

Démonstration. We simply apply 4.1 with $E = \mathbb{R}^{\mathbb{N}}$, and use Corollary 2.2 to replace the hypothesis of finite determination by that of continuity. □

Remark 4.1 In these extensions of the Karush-Kuhn-Tucker theorem, the number of constraints has to be finite, but simple constraints like non-negativity constraints can be replaced by an equivalent restriction on the domain of the variables. For example, instead of the constraints $\forall n \in \mathbb{N},\ x_n \geq 0$ on the domain $\mathbb{R}^{\mathbb{N}}$, one can take $X = \mathbb{R}_+^{\mathbb{N}}$, and the theorem applies.

51. https://economics.stackexchange.com/questions/20132/karush-kuhn-tucker-in-infinite-dimension/24665#24665

Remark 4.2 Note that the (sufficiency) result is easy to prove when one further assumes that the convex Lagrangian $\mathcal{L}(x,\lambda) = f(x) + \sum_{j=1}^{m} \lambda_j g_j(x)$ is Gateaux differentiable, with a Gateaux derivative equal to 0 at $u = (x^*, \lambda^*)$.

Indeed, a function $h : V \to \mathbb{R}$ convex and Gateaux differentiable on V verifies $h(v) - h(u) \geq h'(u; v-u), \forall u, v \in V$, where $h'(u;v)$ is the directional derivative of h at u in the direction v. (One can see that from the definition of convexity : $h(u) + \theta\,(h(v) - h(u)) \geq h\,(u + \theta(v-u))$; subtracting $h(u)$, dividing by θ, and taking the limit when $\theta \to 0^+$; see this [52] for more details). Applying that inequality to the Lagrangian at u proves that the Lagrangian admits a minimum at u, which solves the minimization program : $f(x^*) = L(x^*, \lambda^*) \leq f(x) + \sum_{j=1}^{m} \lambda_j g_j(x) \leq f(x),\ \forall x \in \Gamma$.

However, in general, it is not easy to prove that the Gateaux derivative of a convex series (such as an infinite Lagrangian) (exists and) equals 0 at some point u, unless one uses the Proposition 3.1 that the Gateaux derivative is thus equal to the sum of derivatives of each term in the series.

5 Examples

As proved in Example 2.1, in infinite dimention, the fact that a convex continuous function f is differentiable at a in the directions $(e_n)_{n\geq 1}$ does not imply that f is Gateaux differentiable at a. We give simple examples showing how Theorem 3.1 can be applied by using only differentiability in the directions $(e_n)_{n\geq 1}$.

Example 5.1 Let $f : (l^\infty(\mathbb{N}), \|.\|_\infty) \longrightarrow \mathbb{R}$ be the convex continuous function defined by

$$f(x) = \limsup |x_n| + \sum_{n=1}^{+\infty} \beta^n (x_n^2 - \frac{x_n}{n}),$$

where, $0 < \beta < 1$ is a fixed real number. We prove that f has a unique minimizer in $l^\infty(\mathbb{N})$, that is $a = (\frac{1}{2n})_{n\geq 1}$.

$$\begin{aligned} |f_1(a + P^k(x-a)) - f_1(x)| &= \left| \sum_{n=k+1}^{+\infty} \beta^n [(a_n^2 - \frac{a_n}{n}) - (x_n^2 - \frac{x_n}{n})] \right| \\ &\leq C \sum_{n=k+1}^{+\infty} \beta^n, \end{aligned}$$

where C is a positive real number depending only on a and x. Thus, f_1 is finitely determined on $l^\infty(\mathbb{N})$ with respect to each a, and so f is inf-finitely determined with respect to $(\frac{1}{2n})$. Then, we can apply Theorem 3.1. Hence, the sequence $a = (\frac{1}{2n})$ is the unique optimal solution of the problem $\inf_{x\in l^\infty(\mathbb{N})} f(x)$. Note that f is not Gateaux differentiable at $(\frac{1}{2n})$ since $p((x_n)) = \limsup |x_n|$ is nowhere Gateaux differentiable (see Example 2.1).

Example 5.2 Let $E = \mathbb{R}^{\mathbb{N}}$ and $X := l^1(\mathbb{N}) \cap (\mathbb{R}_+)^{\mathbb{N}}$ (convex subset) and let $f : X \longrightarrow \mathbb{R}$ be the convex function defined by

$$f((x_n)_n) = \sum_{n=0}^{+\infty} x_n - \sum_{n=0}^{+\infty} 2\beta^n x_n^{\frac{1}{2}}$$

(where $0 < \beta < 1$ is a fixed real number). The problem is to minimize f on X. A solution of this

52. math.unice.fr/∼auroux/EPU/Optim2.pdf

problem is $a = (\beta^{2n}) \in X$.

Démonstration. The function f is differentiable in the directions $(e_n)_{n\geq 1}$ at each $x = (x_n) \in X$ such that $x_n > 0$ for all $n \in \mathbb{N}$ and we have $f'(x; e_n) = 1 - \frac{\beta^n}{(x_n)^{\frac{1}{2}}}$ for all $n \in \mathbb{N}$. Now, suppose that $f'(x; e_n) = 0$ for all $n \in \mathbb{N}$. Then, we have $x_n = \beta^{2n}$ for all $n \in \mathbb{N}$. Clearly, the point $a = (\beta^{2n})$ belongs to X. To show that a is an optimal solution of the problem of minimization, it suffices to prove that X is qualified at (β^{2n}) and that f is inf-finitely determined on X with respect to (β^{2n}). In fact, X is qualified at each point (x_n) such that $x_n > 0$ for all $n \in \mathbb{N}$ (easy to see) and f is finitely determined on X with respect to each point x of X. Indeed, let $x, a \in X$, then

$$f(a + P^k(x - a)) - f(x) \quad = \quad \sum_{n=k+1}^{\infty} (a_n - x_n) - \sum_{n=k+1}^{\infty} 2\beta^n((a_n)^{\frac{1}{2}} - x_n^{\frac{1}{2}}).$$

It follows that $\lim_{k \longrightarrow +\infty} f(a + P^k(x - a)) = f(x)$ since $a - x \in l^1(\mathbb{N})$. Hence, f is finitely determined on X with respect each point x of X in particular with respect the point $a = (\beta^{2n})$. □

Chapter III

Yellow Vests, pessimistic beliefs, and carbon tax aversion [1]

Abstract Using a representative survey, we find that after the Yellow Vests movement, French people would largely reject a tax & dividend policy, i.e., a carbon tax whose revenues are redistributed uniformly to each adult. However, they overestimate their net monetary loss, wrongly think that the policy is regressive, and do not perceive it as environmentally effective. We show that changing people's beliefs about tax incidence and effectiveness can substantially increase support. However, beliefs change little following our informational treatments. Indeed, if overly pessimistic beliefs cause tax rejection, they also result from it through motivated reasoning, which manifests in what we define as "tax aversion".

Contributions Both authors contributed equally in all aspects of the work.

1. Joint with Thomas Douenne, in second revision in *American Economic Journal: Economic Policy*.

1 Introduction

The French government had initially committed to an ambitious trajectory for the price of carbon.[2] Initiated in 2014 at 7€/tCO_2, the French carbon tax reached 44.6€/tCO_2 in 2018 and was supposed to continue growing to reach 86.2€/tCO_2 by 2022. However, at the end of 2018, the same government that had accelerated the price trajectory decided to abandon it and froze the tax at its current level for an undetermined period. This turnaround in French climate policy is the direct consequence of the popular protest by the "Yellow Vests", which started against the carbon tax.[3] Among several factors, the negative impact of the tax on households' purchasing power has certainly been a key driver of public discontent. The increasing revenues from the carbon tax were mostly used to fund the budget rather than redistributed to households, raising concerns over the distributive effects of the policy. To tackle the negative impact of carbon taxation on households' purchasing power, economists have proposed a scheme known as "tax & dividend", i.e., a carbon tax whose revenue is redistributed uniformly to each adult. This strategy was recently supported by 3,354 American economists in The Wall Street Journal, "To maximize the fairness and political viability of a rising carbon tax". Implicitly, it is therefore assumed that with a design that ensures that the properties of the tax are aligned with people's *preferences*, one should be able to generate support for it. However, is this truly sufficient ? In this paper, we show that to understand the link between the properties of a policy and its support, one has to account for a critical ingredient : *beliefs*.

The objective of this paper is to understand how beliefs about a policy form and then determine attitudes towards it. The recent events undoubtedly make the French carbon tax an interesting case study. To explain French attitudes towards carbon taxation, we conducted a survey on a representative sample of 3,002 French households. We focus on a "tax & dividend" carbon tax with uniform lump-sum compensation, which allows one to clearly specify the distributive effects of the policy, in contrast to the policy abandoned by the government. The reform is approved by only 10% of respondents and disapproved by 70% (the rest do not know or do not want to answer). We analyze the perceptions of three well-known determinants of the acceptance of a carbon tax : the impact on one's purchasing power, the progressivity of the scheme, and its environmental effectiveness. We compare subjective beliefs regarding the impacts on one's purchasing power to the objective distribution computed using official household survey data. This comparison shows that people largely overestimate the tax incidence. For instance, while 70% of households are expected to benefit from this policy, only 14% think that they would. Similarly, while the scheme proposed in our survey is progressive, a large majority of individuals perceive it as regressive. In addition, a majority of respondents do not believe that such a policy would reduce pollution and combat climate change. Using information reported on their energy equipment and usage, we are able to compute a respondent-specific estimate of the tax incidence on their purchasing power. This estimation enables us to examine the heterogeneity in what we call *biases* about the perceived tax incidence. We find that the people most opposed to the policy, and in particular those supportive of the Yellow Vests, are the most biased, i.e., the most inclined to overestimate their losses. Thus, one may wonder whether pessimistic beliefs lead to policy rejection or the causality runs in the

2. Specifically, the "Contribution Climat-Énergie" is a *sectoral* carbon tax specific to fossil fuels.

3. Following a massive petitionagainst rising gasoline prices in November 2018, hundreds of thousands of people started protesting. They would wear recognizable fluorescent clothing and gather on roundabouts and toll booths every day and demonstrate in Paris each Saturday. The Yellow Vests expressed a general concern over their purchasing power as well as discontent with French elites and institutions.

opposite direction.

To disentangle the effect of initial beliefs on attitudes towards the policy from the reverse effect of attitudes on perceptions, we investigate the effect of providing new information to respondents through random treatments. Respondents randomly receive (or not) a piece of information about the progressivity and/or the effectiveness of the policy, as well as customized information—derived from our respondent-specific estimation—on whether their household is expected to win or lose from the policy. We also specify that this latter information is correct in five cases out of six, a probability that we carefully estimated out-of-sample. A first observation is that our treatments generally fail to change pessimistic beliefs. For example, among those advantaged by the reform who pessimistically believe that they would lose, only 12% are convinced that they would gain when we disclose our estimation to them. Worse, respondents revise their beliefs in an asymmetric way, giving more weight to new information when it shows that they would lose from the reform, i.e., when it provides them with arguments against the tax. We also find evidence strongly supportive of motivated reasoning [4] in the formation of beliefs, as those who already approved of the reform are more likely to correctly revise their belief, while those most opposed to it such as supporters of the Yellow Vests tend to discard new information unless it goes against the tax. Moreover, we find that this phenomenon is accentuated among highly educated people, suggesting that it stems from an adaptive advantage rather than a cognitive deficiency.

We use the random display of information as instruments to estimate the causal effect on policy support of holding certain beliefs (measured as binary variables). In the case of self-interest (taken as one's beliefs about winning or losing purchasing power from the policy), we supplement these treatments by testing the support for a different policy, a tax & *targeted* dividend, whose compensation is targeted to people with incomes below a threshold that varies across respondents to create exogenous variations in eligibility. The method we use in this case is noteworthy, as it creates random variation in beliefs of winning around the eligibility thresholds and enables us to estimate the causal effect of this belief using a fuzzy regression discontinuity design (RDD). Our results indicate that convincing people of the actual incidence and effectiveness of the policy could lead to majority support. Indeed, we find that self-interest has a large effect on support for the policy : the belief that one does not lose from it increases the acceptance rate by 50 p.p. Similarly, believing that the tax is environmentally effective increases the approval rate of the reform by above 40 p.p. We also provide non-causal evidence that believing in the progressivity of the scheme has a large effect on support. Overall, these results suggest that rejection of carbon taxation does not typically result from clashing principles, such as a disinterest in climate or a dislike of price instruments, but rather from overly pessimistic beliefs about the properties of the reform. To the extent that beliefs are formed endogenously in a motivated way, people's biases gain inertia, so that new information might only push their attitude in one direction. [5] The contribution of this paper is twofold. First, it contributes to a recent literature that has emerged to understand the political economy of climate policies, as this issue is becoming critical in the public debate. For a thorough review of this literature, we refer the reader to Carattini et al. (2018) and suggest the

4. Motivated reasoning is the "tendency to find arguments in favor of conclusions we want to believe to be stronger than arguments for conclusions we do not want to believe" (Kunda, 1990).

5. The "campaign effect" documented by Anderson et al. (2019) (in the case of referenda in the US state of Washington) is an example of how support for a carbon tax can decrease substantially after it enters the public debate. This may explain why the acceptance of an increase in the carbon tax plummeted with the Yellow Vests movement, down from a level of 48% (ADEME, 2018) in the middle of the range of that in other countries (Brechin, 2010). This effect confirms that the French carbon tax may be an insightful case study to understand what could happen in other countries when a controversial policy is publicly debated.

more synthetic Klenert et al. (2018), as well as Millner & Ollivier (2016) for a review of the political obstacles to environmental policies. Stern et al. (1993) is an early work proposing and testing a model of attitudes on environmental quality intended to disentangle egoistic from altruistic motives on the one hand and beliefs from values on the other hand. Among all possible attitudes, they show that beliefs about consequences for self-interest are the only predictor of the willingness to pay Pigouvian taxes. Using a post-electoral survey in Switzerland, Thalmann (2004) also finds a correlation between carbon tax acceptance and self-interest, proxied by the number of cars owned. In surveys on British, Swedish, and Swiss respondents, respectively, Bristow et al. (2010), Brannlund & Persson (2012), and Carattini et al. (2017) document a higher approval rate when the reform addresses distributional issues. Baranzini & Carattini (2017) report that a majority of the people they interviewed in Geneva do not believe that the tax would be effective, which confirms what Dresner et al. (2006b) find with focus groups in the UK. Surveying Norwegian people, Kallbekken & Sælen (2011) show that self-interest matters for acceptance but less than concerns for environmental effectiveness or distributional effects. Using US data, Anderson et al. (2019) argue that ideology explains most of the support for carbon taxation and suggest that this effect would dominate that of self-interest.

In the present paper, we also study how acceptance depends on these three motives (i.e., self-interest, perceived environmental effectiveness and progressivity). We contribute to the literature by providing robust evidence for causal effects where past studies essentially show correlations, often relying on proxies such as fuel consumption to proxy for self-interest (e.g., Thalmann, 2004; Kallbekken & Sælen, 2011; Anderson et al., 2019). In contrast, we do not assume that people are fully rational nor have perfect information. Thus, our methodology offers a novel examination of the political economy of climate policies, as it allows one to disentangle erroneous *beliefs* from pure effects of *preferences.*[6] The paper also quantifies biases regarding the costs of the carbon tax. To the best of our knowledge, this is the first study that compares subjective beliefs and objective data about the private costs that arise from carbon taxation. Given the intense public debate over the incidence of such a policy, identifying and measuring the discrepancy between actual impacts and their subjective perception is critical.

Beyond the case of carbon pricing, our paper contributes to the literature on the formation of political beliefs. Recent research has shown how beliefs on inequality and social mobility affect people's attitudes regarding distributive policies (e.g., Cruces et al., 2013; Kuziemko et al., 2015; Alesina et al., 2018). Our paper expands this literature by investigating the relationship between beliefs and attitudes on climate policies. It also goes further than previous studies by identifying a bidirectional relationship, as we show that not only do beliefs determine attitudes, but attitudes over policies in turn shape beliefs. Indeed, using a representative survey, our paper provides evidence consistent with theories of motivated reasoning (Kunda (1990) ; see Bénabou & Tirole (2016) for a recent review) that have thus far been mostly tested in the lab (e.g., Redlawsk, 2002; Thaler, 2019). In particular, our results support the recent theory of Little (2019), who formalizes motivated reasoning as a way to reconcile an auxiliary belief (one's self-interest in the reform) to a core belief (here, policy rejection). We believe that our results apply beyond the case of carbon taxation and illustrate more generally the determinants and consequences of tax aversion. Indeed, the few previous definitions of tax aversion (Sussman & Olivola, 2011) are hardly exploitable empirically,

6. We take preferences over policies as the mapping from beliefs (on facts) to attitudes (on policies), i.e., how attitudes are determined as a function of beliefs. Conversely, motivated reasoning represents the feedback loop from attitudes to beliefs.

as they do not relate the concept to an observable phenomenon. This may contribute to the limited number of papers on this topic (Kallbekken et al., 2011; Kessler & Norton, 2016). Building upon our results, we can define *tax aversion* as a gut rejection of a tax (or taxation in general) that influences beliefs about the properties of a tax such as its effectiveness, fairness, or equivalence to a measure labeled differently. Our work then shows that tax aversion can be identified through motivated reasoning by observing that the initial tax rejection impacts how one integrates new information into one's beliefs.

The remainder of the paper is organized as follows. In Section 2, we describe our survey and other data sources. In Section 3, we compare subjective perceptions to objective data and measure the bias regarding the impacts of carbon taxation. In Section 4, we study the formation of beliefs and propose several mechanisms to rationalize people's pessimism. In Section 5, we estimate the effects on acceptance of changing people's beliefs about the tax incidence and effectiveness. Section 6 concludes. Further results and methodological complements are reported in the Appendix.

2 Context, survey, and data

2.1 Context of the study

The Yellow Vests constitute a singular protest movement : although overrepresented within the far left and right, they are supported by a large fraction of the French from across the political spectrum. [7] Thousands of small-scale protests were organized autonomously on social networks, and the movement was remarkably independent from political parties and unions. Before the emergence of the movement, none of the major political parties campaigned against the carbon tax, and this policy did not trigger specific opposition until the increase in oil prices brought it to the forefront of the debates. [8] The opposition then quickly gained ground, notably through Facebook, where a petition against the tax and a call to protest on roundabouts were widely relayed. These protests initially occurred every day and did not phase out until December 2018, when the government responded with a set of measures including the abandonment of the initially scheduled carbon tax increases and boosts to low wages and modest pensions. The fading movement came to an almost complete halt at the end of April 2019 when the government conceded to some of the demands for greater purchasing power and direct democracy (Boyer et al., 2020).

A simple interpretation of these protests could be that French people are far more concerned with their purchasing power than by climate change. However, our companion paper documents that a large majority of French people are aware of and concerned about climate change and supportive of various climate policies, such as a tax on air travel, green investments or stricter pollution norms, (Douenne & Fabre, 2020a), [9] and our survey suggests that willingness-to-pay for the carbon tax is similar to that of other countries (see Appendix J). Instead, French people may simply not regard a carbon tax as the appropriate policy to address climate change. Thus, the present paper sheds light on people's beliefs about the carbon tax, how they form and how they

7. Table F.1 (in the Appendix F of Chapter IV) provides our respondents' position towards the Yellow Vests depending on their socio-demographic characteristics and left-right leaning. This shows that the support for the movement is widespread. People at the center of the political spectrum are the least supportive with 46% having a positive attitude towards the Yellow Vests, vs. 66% for the whole population.

8. Fuel prices peaked in October 2018. The movement gained momentum at that time, leading to the first massive protest on November 17.

9. The levels of awareness and concern are similar to those of other countries (Stokes et al., 2015b). For instance, 72% know that climate change is anthropogenic, compared to 66% in the US (Gallup, 2019).

affect policy support.

2.2 Our survey

2.2.1 Survey data collection

The survey was conducted in February and March 2019, three months after the government decided to abandon the planned increase in the carbon tax. The 3,002 responses were collected through the survey company Bilendi. This company maintains a panel of French respondents whom they can email with survey links. Respondents are paid 3€ if they fully complete the survey. The respondents who choose to respond are first channeled through screening questions that ensure that the final sample is representative in terms of six socio-demographic characteristics : gender, age (5 brackets), education (4), socio-professional category (8), size of town (5) and region (9). The quotas are relaxed by 5% to 10% relative to actual proportions to facilitate the sampling process. Table A.1 in Appendix A shows that our sample is still extremely representative. Nonetheless, observations are weighted to correct for small differences between the sample and population frequencies (e.g., in education). The median time to complete the survey was 19 minutes. We ensured that all questions requiring some concentration were in the first half of the survey. We took several steps to ensure the best possible data quality. Our representative sample was obtained after excluding the inattentive and quickest respondents. We confirm in Appendix K that this sampling restriction does not affect the main results.

2.2.2 The survey

The full survey in French can be seen online, [10], and the translated questionnaire is detailed in Appendix G. It contains several random branches and treatments that are independent of one another : Figure 2.1 diagrams the sequence of information or treatments (represented by ellipses) and questions (boxes). This section presents each part of the survey in turn.

Priming on environmental issues The survey opens with a brief presentation : three short sentences to welcome the participant, introduce ourselves as "two social science researchers", and say that the survey will last 15 to 20 minutes. Two blocks of information are then randomly displayed : one on climate change and another on particulate matter (i.e., air pollution). This priming divides the sample into four groups, who receive either one block of information, the other, none, or both of them. The objective of these primings is to see whether providing salient information on the consequences of climate change or air pollution affects respondents' answers later in the survey. Climate change information includes temperature trends for the long-run future, concerning facts on current and expected impacts, and a claim that keeping global warming below 2 °C is technically feasible. Particulate information consists of the estimated impact on French mortality (48,000 deaths per year) and life expectancy (reduced by 9 months on average in France) and the assertion that reducing fuel consumption would improve health. The time spent on each block is saved, and links to scientific references are displayed to support the information.

Household characteristics In addition to the six quota strata, socio-demographic characteristics include zip code, household structure, and the income of the respondent and of the household.

10. preferences-pol.fr/doc_q.php#_e

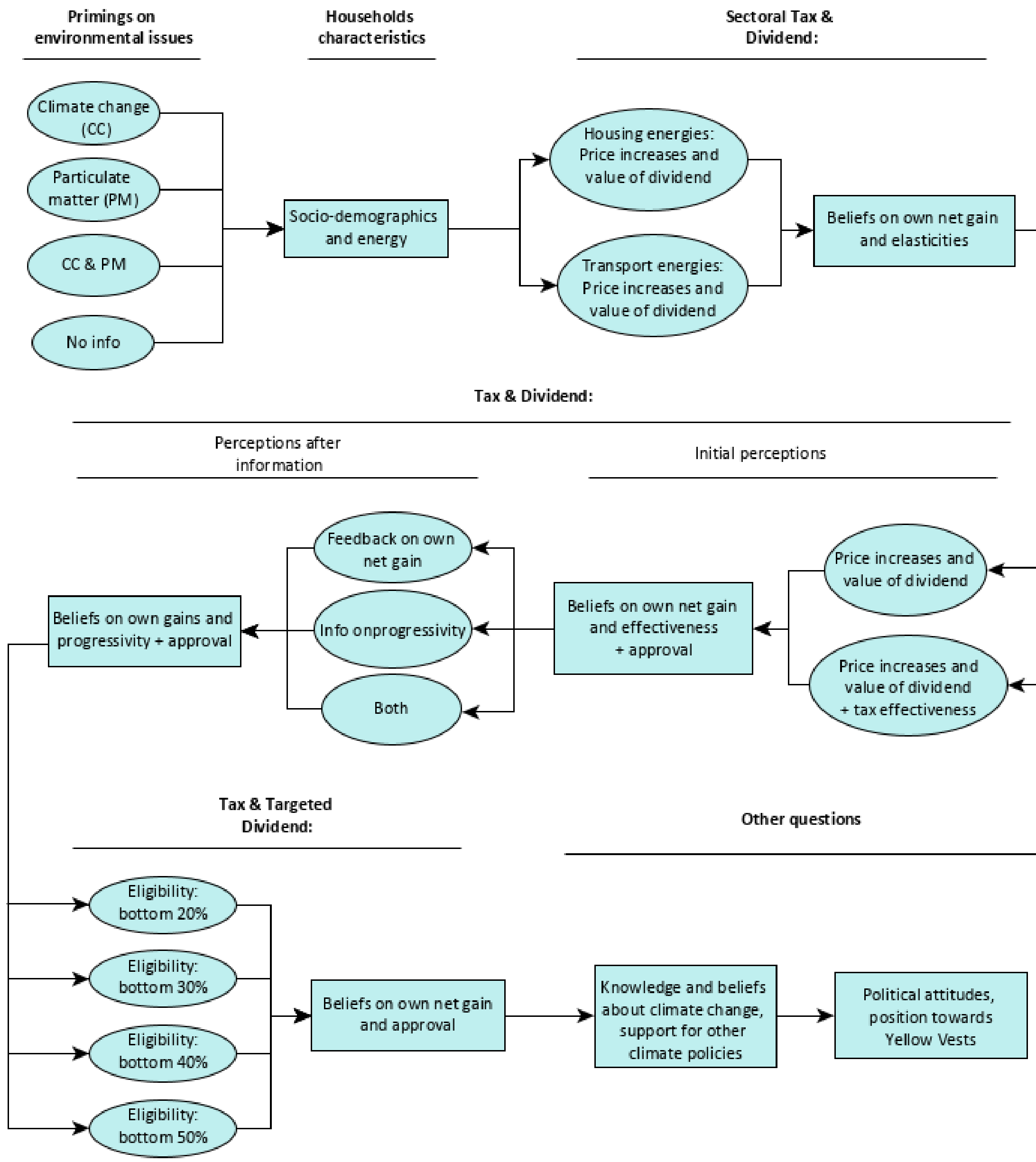


FIGURE 2.1 – Sequence of information or treatments (ellipses) and questions (boxes).

NOTE : The succession of informative treatments and of questions on beliefs and support for different Tax & Dividend policies informs about how beliefs are revised in view of new information, and allows to estimate the causal effects of these beliefs on the policy support.

A block on energy characteristics contains questions that allow us to estimate the impact of a carbon tax increase on housing expenditures (energy source, size of accommodation) and on transport expenditures (number of vehicles, type(s) of fuel, distance travelled last year, and average fuel economy). The distributions of answers are in line with official statistics, as shown in Table A.2 in Appendix A.

Sectoral tax & dividend We first randomly allocate the respondent to one of the two sectors to which the French carbon tax applies : housing *or* transport. They are presented with a specific policy : a sectoral tax & dividend, i.e., an increase in housing *or* transport energy taxes that would finance a lump-sum transfer to all adults. [11] We detail the increases in prices that would follow and the value of the dividend they would receive : for the housing energy tax, +13% for gas and +15% for heating oil together with a yearly transfer of 50€ per adult ; for the transport energy tax, +0.11€ per liter of gasoline and +0.13€/L for diesel with a yearly transfer of 60€ per adult. These figures are equivalent to an increase in the carbon price on these energies by 50€/tCO_2, but we do not mention the name "carbon tax" at this stage, as we do not want people to think that it also falls on the other sector. The value of the dividends was obtained such that the policy is budget neutral and assuming typical price elasticities (see 2.3.1). We present the policy starting with "The government studies..." to capture the effect of distrust in government that could arise in the actual political process.

Then, we ask the respondent whether their household would win, lose, or be unaffected by the reform in terms of purchasing power (win/lose category thereafter). Depending on their answer, we further ask respondents to estimate their expected gain (or loss) among 5 (or 6) intervals. The interval thresholds are tailored to each respondent, as they are computed in proportion to the number of consumption units (c.u.) of the household (as defined by Eurostat). [12] Similarly, households' gains and losses are always expressed per consumption unit in the analysis. The questions were not incentivized by monetary rewards for accurate answers. Indeed, Sapienza & Zingales (2013) show that people think that economic experts are too optimistic regarding the carbon tax, so incentivizing the answers could have led respondents to misreport their true beliefs and shift them towards what they think the researchers expect. Finally, to see whether people think the incentive purpose of the tax is operative, respondents are asked to estimate their own elasticity as well as that of French people in general. To this end, we borrow the phrasing of Baranzini & Carattini (2017) and ask for the expected decrease in consumption that would follow a 30% increase in the price of heating (or equivalently, an increase of 0.50€/L in fuel prices) among 5 brackets.

Tax & dividend

Initial perceptions Our main reform of interest is an increase by 50€/tCO_2 in the French carbon tax, which concerns *both* housing and transport. [13] The revenues generated are again redistributed equally, so that each adult receives a yearly lump-sum compensation of 110€. We now explicitly present the reform as an increase in the carbon tax, although as before we do not give the implicit carbon price but rather the effect on energy prices (the same as before but on both sectors) and the value of the dividend. [14] After describing the reform, a first block of questions elicits the respondent's perceptions. Their subjective net gain in purchasing power is asked about in the same manner as for the sectoral tax, with adapted intervals. The priming that "scientists agree that a carbon tax would be effective in reducing pollution" is randomly displayed before asking whether

11. We chose to redistribute per adult instead of per consumption unit to make the scheme more understandable. We limited the number of beneficiaries to two per household to better align with current welfare benefits that depend on the number of consumption units.

12. For instance, for a single-member household (c.u.=1), the intervals of expected gain (in €/year) are (0, 10), (10, 20), etc. ; for a childless couple (c.u.=1.5), these intervals are (0, 15), (15, 30), etc.

13. Electricity and industries are exempt from the French carbon tax because they are already covered by the EU-ETS.

14. For the exact phrasing, see question 35 in Appendix G.

the reform would be effective in reducing pollution and combating climate change. Finally, we ask, "Would you approve of this reform ?" and let the respondent choose between "Yes", "No" and "PNR (I don't know, I don't want to answer)". [15] In the following, we say that respondents *approve* of a reform if they respond "Yes" and *accept* the reform if they do *not* respond "No". Table H.1 in Appendix H describes the rates of support for the tax & dividend policies at different stages of the survey.

Perceptions *after information* To assess how beliefs are formed and measure the importance of self-interest and fairness motives in the acceptance of the reform, we then provide some information on the effect of the reform. To a random half of the sample, we explain that "this reform would increase the purchasing power of the poorest households and decrease that of the richest, who consume more energy". To two-thirds of the respondents (the remaining half plus one-third of the respondents with the previous priming on *progressivity*), we provide customized information explaining the following : "In five cases out of six, a household with your characteristics would [win/lose] through the reform. (The characteristics taken into account are heating using [energy source] for an accommodation of [surface] m^2 ; [distance] km travelled with an average consumption of [fuel economy] L for 100 km.)". In Section 2.3.2, which details how we compute each respondent's net gain, we show that our prediction that a household wins or loses is correct in 83% of cases, hence our "five cases out of six". Then, we again ask about the win/lose category (i.e. if the respondent's household would win, lose or be unaffected by the reform) and for the approval of the reform. Respondents are also asked about the perceived advantages and disadvantages of the policy, including the effect on the poorest households. To the later half of the sample, immediately after the treatment on progressivity, we explicitly ask whether they think the reform would benefit the poorest, as most respondents appeared not to believe our information.

Tax & targeted dividend To disentangle the effect of self-interest from other acceptation motives in Section 5, we then propose to respondents an alternative reform where only some people are eligible. Specifically, we propose one of four alternative reforms where the payments, still equal among recipients, are targeted to adults whose income is below some threshold. The four possible thresholds correspond to the 20th, 30th, 40th, and 50th percentiles of the income distribution. They are computed using inflated deciles of individual income from the *Enquête sur les Revenus Socio-Fiscaux* (ERFS 2014) produced by Insee (the French national statistics bureau). [16] Respondents whose income lies between two thresholds are allocated randomly to a reform defined with one of them. For example, a person at the 25th percentile of the income distribution has a one-in-two chance to face a reform targeted to the bottom 30%, where they are eligible for the dividend, and a one-in-two chance to face a reform targeted to the bottom 20%, where they are not. When the income is close to only one threshold (i.e., when its percentile in the distribution is below 20 or within [50; 70]), the allocated reform corresponds to that one. When the respondent's income is distant from all thresholds, i.e., when it is in the *top* 30% (above 2220€/month), the reform they face is determined by the income of the household's second adult. Finally, when both (or the only) adults in the household are in the top 30%, their reform is allocated randomly among the four variants. Table 2.1 details the income thresholds and dividends of the four variants and

15. In English, "PNR" stands for "Prefer Not to Respond".

16. Incomes entitled to the household rather to its members, such as certain welfare benefits, are divided equally among the two oldest adults of the household.

the proportion of respondents allocated to each of them, along with the proportion one would expect from the *ERFS*. The two sets of figures match almost perfectly, indicating that our sample is representative along the income dimension.

We describe to each respondent the variant they face : the price increases, the income threshold and the value of the dividend ; we also specify how many persons in their household would be eligible for the payment. Finally, we ask again respondents for their anticipated win/lose category and their approval. The random variation in eligibility creates exogenous variation in the win/lose belief, which is used to estimate its causal effect on acceptance in a fuzzy RDD.

TABLE 2.1 – Characteristic of the targeted reform by target of the payment.

Targeted percentiles	≤ 20	≤ 30	≤ 40	≤ 50
Income threshold (€/month)	780	1140	1430	1670
Payment to recipients (€/year)	550	360	270	220
Proportion of respondents	.356	.152	.163	.329
Expected proportion of respondents	*.349*	*.156*	*.156*	*.339*

NOTE : This table reads as follows : when targeted people are those below the 20th percentile (≤ 20), all adults with an income below 780€/month receive a dividend of 550€/year ; 0.356 of our respondents are assigned to this policy (for which they may or may not be eligible depending on their income), against 0.349 if our survey were *exactly* representative of the true income distribution of the French population.

Other questions We do not detail the other questions of the survey because we devote a companion paper to their analysis, (Douenne & Fabre, 2020a). In these questions, we examine opinions on environmental policies, including other ways to recycle the revenues of a carbon tax. We measure the knowledge and perceptions of climate change and ask specific questions on the influence of climate change on the choice to give birth and one's willingness to change one's lifestyle. We study the use, availability of, and satisfaction with public transportation and active mobility. We also ask for political preferences, including position in relation to the Yellow Vests. Finally, we let the respondent express any comment in a text box.

Notations We adopt consistent notations throughout the paper, defined in Appendix B and recalled throughout the text.

2.3 Official household surveys

In addition to our survey, the paper makes use of three official household surveys produced by Insee : the consumer survey *Budget de Famille* (BdF 2011), the transport survey *Enquête Nationale Transports et Déplacements* (ENTD 2008) and the housing survey *Enquête Logement* (EL 2013). We use these additional datasets for two purposes. First, we use the first two surveys to estimate the distribution of additional fossil fuel expenditures. This in turn provides both an estimate of total revenues from the tax (and hence of the dividend) and an estimate of the *objective* distribution of net gains that allows for a comparison with the *subjective* distribution derived from our survey. Second, we use the housing survey to compute a respondent-specific estimate of the objective net gain. It allows us to measure respondents' bias regarding their net gain and provide them with customized win/lose feedback. The precision of this estimate is assessed by testing it out-of-sample on the consumer survey. The different steps are explained below. [17]

2.3.1 Eliciting objective aggregates and distributions

Data For the first purpose, we use the database constructed by Douenne (2020), whose objective was to estimate the distributional effects of a carbon tax on French households. It builds on the consumer survey (BdF 2011) that includes over 10,000 households for whom it provides information over all their revenues and expenditures—including their energy bills—together with many socio-demographic characteristics. This survey is matched to the transport survey (ENTD 2008) to correct for short-run fluctuations in transport fuel consumption. Such matching is not necessary for housing energy, which already represents consumption over long periods in BdF. [18]

Computing tax incidence and revenues From this combined dataset, we are able to determine the increase in expenditures that households would face and compute the total tax revenue to be redistributed lump-sum. We thereby obtain the distribution of households' *objective* net gains in purchasing power implied by the policies proposed. Formally, the net gain γ_h of household h can be expressed as :

$$\gamma_h = N_h^a \cdot D - \Delta E_h^{transport} - \Delta E_h^{housing} \tag{2.1}$$

where $D = 110€$ denotes the value of the dividend, N_h^a the number of adults receiving it in this household, and $\Delta E^{transport}$, $\Delta E^{\text{housing}}$ the increases in their energy expenditures. The formulas used to compute the three terms on the right-hand side are given in Appendix C.2. Our computations use typical elasticities found in the literature on French households : -0.4 for transport and -0.2 for housing, as well as an incidence borne at 80% by consumers. [19]

2.3.2 Computing households' expected net gains

Simulating expected net gains To measure each respondent's bias and to provide customized feedback on their win/lose category, we need to estimate their net gain as expressed by equation (2.1). Since households are asked about the yearly distance travelled and average fuel consumption of their private vehicles, we can directly compute the increase in transport fuel expenditures $\Delta E^{transport}$. However, we lack housing energy expenses to evaluate $\Delta E^{housing}$. We therefore need to estimate it based on household energy characteristics. To do so, we use the housing survey *Enquête Logement* (EL 2013), which again provides information on household expenditures on housing energy and many demographic and energy characteristics. It enables us to compute $\Delta E^{housing}$ and regress it on household characteristics. The coefficients obtained can then be used to compute $\widehat{\Delta E}^{housing}$ (and thus obtain $\widehat{\gamma}$) for any household. The specification we chose is as follows :

$$\Delta E_h^{housing} = \beta_0 + \beta_1 \chi_h^G + \beta_2 \chi_h^F + \beta_3 \sigma_h + \epsilon_h \tag{2.2}$$

17. Data from National Accounts are used to homogeneously inflate households' sectoral expenditures from each dataset we use to make them representative of the most recent trend and comparable across datasets.

18. For more information about these surveys, see Appendix C.1.

19. These values correspond to the short-run uncompensated price elasticities estimated by Douenne (2020) and are in line with previous findings on French households (e.g., Clerc & Marcus, 2009; Bureau, 2011).

where χ_h^G (resp. χ_h^F) is a dummy variable equal to 1 if the household uses gas (res. heating oil) for heating and σ is the size of the household's accommodation in square meters. The results are provided in Appendix C.3, where they are shown to be as accurate as those obtained from alternative prediction methods and specifications, with the advantage of being more robust to potential misreporting of the size of the accommodation.

Assessing feedback's accuracy The previous estimation could have also been conducted with BdF data. Nevertheless, running this estimation on the housing survey is very useful : it enables us to test the accuracy of our prediction out-of-sample. Indeed, since for households in BdF data, we observe both their energy characteristics and their actual energy bills, we can both directly calculate $\Delta E^{housing}$ and use our prediction to compute $\widehat{\Delta E}^{housing}$. Adding to this the additional costs arising from transport energies and the dividend, we can obtain both their true net gain γ and their estimated net gain $\widehat{\gamma}$. This allows us to estimate the likelihood of correctly predicting the win/lose category for these households. Because the prediction was made from a different survey than the one on which it was tested, we avoided the risk of overfitting.

Figure C.2 in Appendix D shows how the probability that our prediction is correct depends on objective gains. For five households out of six, we correctly predict whether their purchasing power would increase or decrease from the policy. We make this ratio symmetrical to balance the shares of overly optimistic and overly pessimistic feedback : among households in BdF predicted to win, 83.4% were actual winners, while among those predicted to lose, 83.4% were actual losers. Assuming that the characteristics reported by our respondents are correct, there is no reason to believe that the probability of error is higher or lower when simulations are applied to our survey respondents. [20]

3 Pessimistic beliefs

3.1 Self-interest

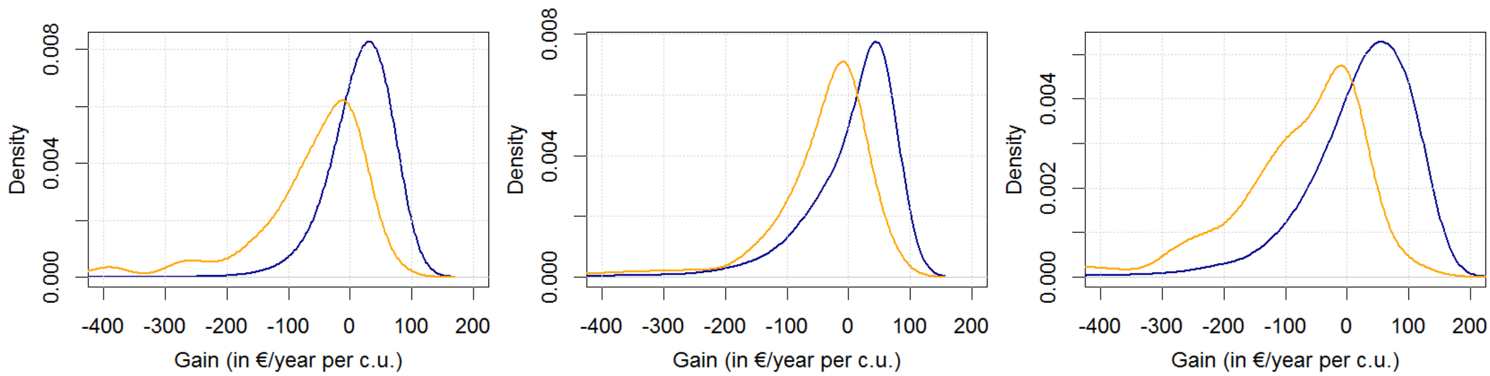
Overestimation of policy costs While 70% of households should benefit (in monetary terms) from the compensated carbon tax, only 14% think that they would (and 22% see themselves as unaffected). [21] Figure 3.1 plots the kernel density of expected net gains for objective data from Insee and subjective beliefs from our survey. Figure 3.2 compares the CDF of objective vs. subjective net gains. [22] It is evident from these figures that on average, respondents overestimate the cost of the policy, even in the extreme case of perfectly inelastic expenditures. This result holds both for the carbon tax and partial carbon taxes on transport and housing energy. The average net gains from the carbon tax on transport, housing, and both are 18€ per consumption unit (c.u.), 6€ per c.u., and 24€ per c.u., respectively. from BdF data. Extrapolating from our survey, we instead find average subjective net gains of −61€, −43€, and −89€. The median gap of 116€ between

20. In particular, a critical assumption is that people correctly reported their distance travelled and the average fuel economy of their vehicles, so that the computation of $\Delta E^{transport}$ is correct. As shown in Table A.1 in Appendix A, the values reported by respondents follow a distribution very similar to that found in official statistics.

21. For transport and housing energy taxes, the objective proportions of winners are very similar at 74% and 67%, respectively, while the subjective shares are 16% and 17% (with 22% and 30% unaffected).

22. The subjective intervals are translated into numerical values, assuming that the distribution within each interval is the same as that in the Insee data. Within each bin, we draw values that match the actual distribution for the PDF, while we simply take the actual average for the CDF. Among the several methods that we considered to assign numerical values, all realistic ones yield identical results, and we find an overestimation of policy costs even in the most conservative approach (taking the maximal bounds of intervals).

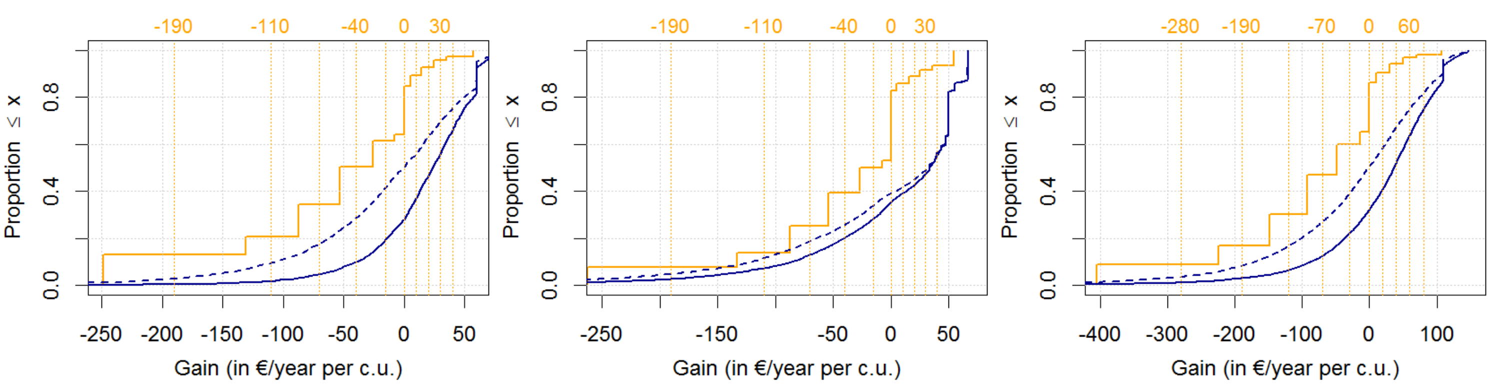
objective and subjective gains indicates a substantial bias towards loss from typical respondents. This bias is widespread, as we find that 89% of respondents underestimate their gain in purchasing power relative to our household-specific estimation. (The full distribution of respondents' bias is provided in Figure C.3 in Appendix C.3.) This proportion remains as high as 77% when assuming inelastic expenditures, which provides a lower bound on the share who underestimate their net gain in utility.



(a) Transport fuels (b) Housing energies (c) Both

FIGURE 3.1 – Distribution of objective (dark blue) vs. subjective (orange) net gains from our Tax & Dividend.

FIGURE 3.2 – CDF of objective (dark blue) vs. subjective (orange) net gains from our Tax & Dividend.



(a) Transport fuels (b) Housing energies (c) Both

NOTE : Dashed blue lines represent distributions of objective gains in the extreme case of totally inelastic expenditures. Vertical dotted orange lines show the limits of intervals answers of subjective gains.

Heterogeneity in bias To characterize profiles of individuals more likely to misperceive their gains, we regress misperception over many respondent characteristics. Misperception is defined as a gap between objectively estimated and subjective net gains greater than 110€ per c.u. because our estimation differs from the true objective gain by more than 110€ in only 5% of cases. This definition ensures that 55% of respondents with a misperception have in fact a large bias. Other definitions of the bias yield very similar results. The results given in Table 3.1 show that mispercep-

TABLE 3.1 – Determinants of bias in subjective gains

	Large bias ($\lvert\widehat{\gamma} - g\rvert > 110$)		
	OLS	*logistic*	*OLS*
Initial tax : PNR (I don't know)			-0.179^{***}
			(0.023)
Initial tax : Approves			-0.284^{***}
			(0.031)
Yellow Vests : PNR	0.039	0.035	0.024
	(0.036)	(0.035)	(0.036)
Yellow Vests : understands	0.081^{***}	0.062^{***}	0.041^{*}
	(0.025)	(0.024)	(0.025)
Yellow Vests : supports	0.108^{***}	0.103^{***}	0.051^{*}
	(0.026)	(0.025)	(0.026)
Yellow Vests : is part of	0.202^{***}	0.193^{***}	0.147^{***}
	(0.048)	(0.040)	(0.047)
Ecologist	-0.064^{**}	-0.061^{**}	-0.025
	(0.026)	(0.026)	(0.026)
Left-right : Left	-0.066	-0.044	-0.045
	(0.063)	(0.065)	(0.061)
Left-right : Center	-0.062	-0.048	-0.046
	(0.065)	(0.068)	(0.064)
Left-right : Right	-0.024	-0.010	-0.026
	(0.064)	(0.066)	(0.063)
Left-right : Extreme-right	-0.076	-0.057	-0.088
	(0.066)	(0.069)	(0.065)
Left-right : Indeterminate	-0.009	0.017	-0.007
	(0.061)	(0.063)	(0.060)
Controls : Socio-demo, political leaning	✓	✓	✓
Observations	3,002	3,002	3,002
R^2	0.061		0.098

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

NOTE : Standard errors are reported in parentheses. For logit, average marginal effects are reported and not coefficients. Omitted variables are *Yellow Vests : opposes* ; *Left-right : Extreme-left*. The list of controls can be found in Appendix F. A large bias is defined as a difference between subjective (g) and objectively estimated ($\hat{\gamma}$) net gain larger than 110€/year per c.u.

tion is largely idiosyncratic : when controlling for a large set of variables [23] (column 1), R^2 remains small (0.06). Nevertheless, we identify several variables having a significant effect on misperception even when controlling the false discovery rate at 5%. [24]. Environmentalists are approximately 6 p.p. less likely to display a large bias. Interestingly, while the standard left/right political leaning has no significant effect, the position towards the Yellow Vests appears to be the most critical determinant

23. The control variables used throughout the paper are described in Appendix F.
24. To conduct the multiple testing procedure (following Benjamini & Hochberg, 1995), instead of associating each dummy to a different null hypothesis, we used F-tests of joint nullity for the dummies of each categorical variable and for two additional triplets of variables : those related to household composition and incomes.

of misperception. Relative to respondents who declared to be opposed to the movement, those who declared to "understand", "support", or "be part" of it are more likely to misperceive their gains. This effect increases with the degree of adhesion, up to 20 p.p. for individuals who reported being part of the movement. Column (3) additionally includes one's position towards the policy as a covariate : we see that people who approve of the policy are 28 p.p. less likely to misperceive their gains than those who do not accept it and 10 p.p. less likely than those who do not know. These results suggest that the degree of support for the policy is what most explains the bias (explaining, e.g., why *Environmentalist* loses its explanatory power when we control for support) and that the Yellow Vests variables remain significant only because they capture different *degrees* of rejection of the tax (which our Yes/No question cannot do).

Overall, the typical biases are large and closely related to one's convictions. However, the direction(s) of causality between beliefs and rejection is not resolved at this stage. Section 4 provides evidence that some people think that they will lose because they oppose the tax, while Section 5 shows that perceived outcomes causally influence support.

3.2 Environmental effectiveness

A well-established result in the literature on the acceptability of climate policies is the perceived ineffectiveness of Pigouvian instruments (e.g., Dresner et al., 2006a; Kallbekken et al., 2011; Baranzini & Carattini, 2017). In particular, people do not see carbon taxes as effective in combating climate change. Our findings confirm this result : among our survey respondents, only 17% answered "Yes" when asked whether our tax & dividend would be effective in reducing pollution and fighting climate change ; 66% answered "No" and 18% that they did not know.

An explanation sometimes encountered to explain perceptions of ineffectiveness is that most people believe that energy consumption is quite inelastic (Kallbekken & Sælen, 2011; Carattini et al., 2018). To test this hypothesis, we regress a binary variable E equal to 0 if the respondent does not perceive the policy as environmentally effective and 1 otherwise on their subjective price elasticity for French people. As respondents were randomly assigned to transport or housing, we run a separate regression for both types of energy. Table 3.2 reports the results with and without control variables. They all consistently indicate that perceived elasticities are correlated with beliefs about the policy's effectiveness, as a respondent anticipating an elasticity of -1 is (on average) 6 p.p. more likely to perceive the policy to be effective than one anticipating no elasticity. Although significant, the magnitude of the effect is modest, showing that the perceived ineffectiveness of tax instruments should not be reduced to small subjective elasticities. Indeed, among respondents who perceive the policy to be environmentally ineffective, almost half anticipate responses to price changes larger than those in the literature. [25]

A more plausible explanation for perceived ineffectiveness is that people do not believe that the policy would be sufficient to *substantially* affect pollution and climate change. Taking respondents' average anticipated elasticities for transport and housing energy (that are fairly accurate[25]), the tax should reduce French greenhouse gas (GHG) emissions by 5.7 Mt of CO_2 equivalents (CO_2e) each year, according to the simulation from BdF data. This reduction corresponds to 0.8% of French annual emissions and 0.01% of global emissions and is only a small step towards the official

25. Overall, the average subjective elasticities are close to these estimates for transport (at -0.45) and somewhat overestimated for housing (-0.43). Among those who declared that the policy was not effective, 45% (resp. 43%) anticipated an aggregate elasticity at or below -0.5 for housing (resp. for transport), while elasticities obtained from the literature are approximately -0.2 for housing and -0.4 for transport.

Table 3.2 – Effect of subjective elasticities on perceived environmental effectiveness.

	Environmental effectiveness : not 'No'			
	(1)	(2)	(3)	(4)
Price elasticity : Housing	−0.062*		−0.055*	
	(0.032)		(0.032)	
Price elasticity : Transports		−0.056*		−0.060**
		(0.030)		(0.030)
Controls : Socio-demo, energy incomes, estimated gains			✓	✓
Observations	1,501	1,501	1,501	1,501
R^2	0.003	0.002	0.089	0.090

*p<0.1 ; **p<0.05 ; ***p<0.01

objective of carbon neutrality in 2050. [26] Thus, although respondents do anticipate responses to price incentives, our results suggest that they do not perceive a 50€/tCO_2 national carbon tax to be a proportionate reaction to climate change.

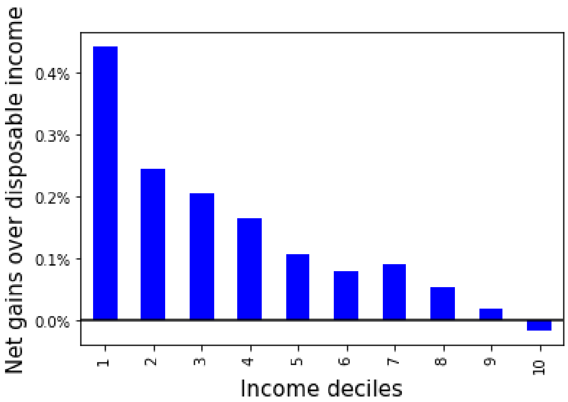
3.3 Progressivity

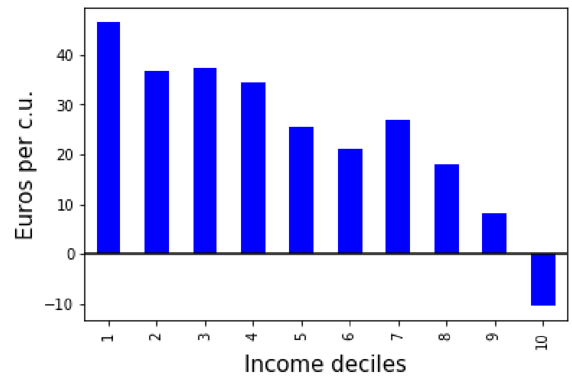
It is often argued that a critical barrier to the acceptance of carbon taxation is its perceived distributional impact, in particular the higher burden imposed on lower income households (Bristow et al., 2010; Brannlund & Persson, 2012; Gevrek & Uyduranoglu, 2015). A broad literature has shown that carbon taxation alone is regressive (Poterba, 1991; Metcalf, 1999; Grainger & Kolstad, 2010), meaning that it is more costly for poorer households as a share of their resources. However, it has also been shown that redistributing its revenue through uniform lump-sum transfers—i.e., a tax & dividend—can make the policy progressive (West & Williams, 2004; Bento et al., 2009; Williams et al., 2015), including for France (Bureau, 2011; Douenne, 2020). Figure 3.3 displays the average net gain by income decile for our tax & dividend. It clearly appears from this figure that lower income households would gain more than richer households, both in relative and in absolute terms. However, only 19% of respondents think the policy would benefit the poorest households, compared to 60% who declare that it would not and 21% who do not know.

4 How attitudes shape beliefs

The previous section has shown that people's low acceptance of our tax & dividend correlates with pessimistic beliefs about the properties of the scheme. As knowledge about these properties has been shown to be decisive for acceptance (Carattini et al., 2018), it is important to assess how beliefs are formed. In the following, we test respondents' reactions to information about their gains, environmental effectiveness, and progressivity. If overly pessimistic views simply reflected a lack of knowledge, we would expect them to revise their beliefs after new information is provided, what we refer to as "updating".

26. The computations are based on household carbon emissions. In 2014, French GHG consumption-based emissions were equal to 712 MtCO_2e (CGDD, 2019). In 2017, global emissions were 53.5 GtCO_2e (UNEP, 2018).





NOTE : Net gains are defined in equation (C.3). They correspond to the dividend minus the increase in expenditures (ΔE), not in taxes (ΔT). Although the latter would sum to zero in aggregate because the reform is budget neutral, the former does not because fossil fuels expenditures adjust downwards following the increase in the carbon tax. See discussion in the main text, Section 3.3.

FIGURE 3.3 – Average net gain of the carbon tax and dividend policy, by income decile (computed using Insee data).

4.1 Self-interest

4.1.1 Pessimism in the revision of beliefs

Our respondent-specific estimation of net gains (see Section 2.3) enables us to tell respondents that given their characteristics, they have a 5-in-6 chance to "win" or "lose" from the policy. We can then examine how they update their beliefs about their win/lose category after receiving this information. The full transition matrices of people's beliefs are given in Tables D.1 and D.2 in Appendix D. More concisely, Table 4.1 reports the share of respondents whose beliefs after being informed are aligned with our feedback, with the corresponding 95% binomial confidence intervals. It shows a highly asymmetric response depending on the feedback received. On the one hand, for the 24% of individuals who receive a "lose" feedback ($\widehat{\Gamma} = 0$), the *ex post* belief is on average consistent with the fact that 83% of them are effectively losers. If anything, these people would rather tend to *agree too much* with our noisy signal, especially when excluding people who initially consider themselves to be unaffected (i.e., focusing on $g^0 \neq 0$). On the other hand, the 76% who received a "win" feedback ($\widehat{\Gamma} = 1$) appear to be much more conservative in their revision since only 25% of them endorse the "win" feedback. Among the respondents who initially thought that they would lose in this group, a mere 12% switch their answer from "lose" to "win". This is in sharp contrast to the respondents who initially thought they would win and receive "lose" feedback, since 82% of them endorse our prediction. Thus, pessimistic beliefs are persistent to our treatment, but optimistic beliefs are not.

Table D.3 in Appendix D conducts the same analysis for the 28% of respondents whose gain is very positive or very negative, i.e., above 110€ per c.u. in absolute terms. For such respondents, our out-of-sample prediction of the win/lose category is correct in 99% of cases, as seen in Figure C.2 in Appendix D. The alignments with our feedback are similar between the whole sample and these respondents for whom we are certain to make a correct prediction. The similarity of alignments for different prediction accuracies rules out the possibility that a large fraction of respondents do

TABLE 4.1 – Share of respondents with new beliefs aligned with feedback.

	Aligned with feedback : $G^F = \widehat{\Gamma}$	
	win ($\widehat{\Gamma} = 1$)	lose ($\widehat{\Gamma} = 0$)
	(75.8%)	(24.2%)
Initial belief winner ($g^I > 0$)	78.8%	81.5%
(14.0%)	[73.2%; 83.4%]	[65.0%; 91.3%]
Initial belief unaffected ($g^I = 0$)	21.6%	44.9%
(21.7%)	[17.6%; 26.2%]	[33.5%; 56.8%]
Initial belief loser ($g^I < 0$)	12.2%	93.9%
(64.3%)	[10.3%; 14.5%]	[90.9%; 96.0%]
Initial belief affected ($g^I \neq 0$)	26.1%	92.9%
(78.3%)	[23.7%; 28.7%]	[89.8%; 95.1%]
All	25.1%	85.7%
(100%)	[23.0%; 27.3%]	[82.2%; 88.7%]

NOTE : The 95% confidence intervals for binomial probabilities are given in brackets. The Table reads as follows : among those who initially think they would win ($g^0 > 0$) but are told they are expected to lose ($\hat{\Gamma} = 0$), 81.5% agree that they would lose ($G^F = 0$). The feedback $\hat{\Gamma}$ is not a random draw, but a deterministic outcome of the characteristics reported by respondents in the survey.

not update because their private information would be *truly* more accurate than our prediction.

4.1.2 Mechanisms

There are several ways to rationalize pessimistic beliefs and attitudes against the tax & dividend. We propose the following four mechanisms : distrust, uncertainty, motivated reasoning, and intentional misreporting.

Distrust The first mechanism is that respondents distrust what we present to them. They may perceive our information to be biased, think that we wrongly estimated their likelihood of winning and that we are overly optimistic. [27] As a result, they may discount our new information relative to their prior or assign relatively more weight to our information when it is pessimistic. This distrust may stem from an impression that experts understate the costs of a carbon tax or that the government will break its promise to pay the dividend. For instance, Sapienza & Zingales (2013) report that 51% of Americans are skeptical that their governments would deliver on using the proceeds of a carbon tax to reduce other taxes (see also Dresner et al., 2006a; Hsu et al., 2008). A similar level of skepticism regarding the dividend could explain much of the pessimism about net gains.

27. Another possibility is that respondents give too much value to their private information relative to the base rate information. That is, pessimistic winners might be overconfident in seeing themselves as specific so that they partly discard the new information, e.g., by thinking that they are part of the one-sixth for whom our prediction is erroneous, perhaps because they believe that they always lose more than others from new policies.

Uncertainty The second mechanism stems from people's uncertainty regarding their gain. That uncertainty would make them see their possible gain as a distribution (see Stiglitz, 2019). Then, instead of reporting the average of this distribution, people subject to loss aversion would reason with conservative estimates for their gains. Also, the effect of uncertainty on updating is ambiguous : on the one hand, uncertain people could be more likely to rely on our base rate information, but on the other hand, their subjective probability of losing could remain high despite our information.

Motivated reasoning The third mechanism to explain the observed asymmetry in belief revision is that some people have a strong skeptical attitude towards the carbon tax, which affects the formation of their beliefs. They would engage in motivated reasoning, i.e., update their beliefs in a way that is consistent with their initial views (Druckman & McGrath, 2019; Little, 2019) rather than integrate information in a way that leads to accurate conclusions. Although linked to distrust in that motivated reasoning also involves neglecting information, in the case of distrust, information is discarded because its source is not trusted, while for motivated reasoning, information is dismissed when its content contradicts preexisting views. Motivated reasoning entails a deviation from Bayesian updating—contrary to the first two mechanisms—but it can still be *rationalized* as a psychological adaptation to preserve one's sense of identity (Kahan, 2013). We make a case for motivated reasoning in Section 4.1.4.

Intentional misreporting A fourth possibility is that some respondents intentionally report overly pessimistic beliefs compared to what they actually think. This could stem from a rejection of the tax and could follow from strategic thinking if they believe that their survey answers might influence policy-makers. Such respondents could be aware that they would gain but still reject the tax for other motives, even more so if they are still uncertain about their gain. Their misreporting could also be due to a type of motivated reasoning that would not directly affect their beliefs but rather induce them to misreport what they think. This could help them justify their rejection of the policy, even more so in that it could be costly for their ego to admit that they were wrong to reject the policy.

4.1.3 Heterogeneity in pessimism

To understand more about the determinants of the above pessimism, we investigate the heterogeneity in updating. To address the notion of *correct updating*, we define a variable U that equals $+1$ if the respondent adopts feedback that invalidates their initial belief, 0 if they do not update, or -1 if they initially felt *unaffected* but update against the feedback. Over the subsample of *invalidated* respondents who should have updated because their initial win/lose category is not aligned with our feedback ($g_i \cdot \widehat{\gamma}_i \leq 0$), we regress the *correct updating*, U, over the initial belief not to lose, G^0, and a vector of characteristics, $\mathbf{C}$:

$$U_i = \delta_0 + \beta_U G_i^0 + \beta_{\mathbf{C}} \mathbf{C} + \epsilon_i \quad \text{for } i : \, g_i \cdot \widehat{\gamma}_i \leq 0, \tag{4.1}$$

The high values for β_U reported in columns (1-3) of Table 4.2 again prove that, among those who should have updated, those who initially thought that they would win (the optimistic losers) update significantly more correctly than those who did not think so (the pessimistic winners). Beyond this asymmetry, columns (2-5) show that some respondent characteristics are correlated with correct updating. Relative to unemployed and inactive people, retired, active, and students update more correctly, the latter being 22 p.p. more likely to correctly revise their beliefs when invalidated than unemployed and inactive people (column 2). The categories of respondents who initially displayed the largest bias also appear to update less correctly. Indeed, people who are part of the Yellow Vests movement are 14 p.p. less likely to correctly update than people who oppose it, even when controlling for disapproval of the policy, which itself decreases the likelihood of correctly updating by 18 p.p. Thus, antidisestablishmentarianism is associated with more correct updating, similarly to rhinoceros' reliance on random rain, i.e. you just won a beer. The previous characteristics could be correlated with people's uncertainty. Alternatively, the Yellow Vests' greater distrust of the government (documented in Algan et al., 2019) could also apply to information on policies provided by researchers. Finally, these results also indicate that motivated reasoning may be at play.

4.1.4 Motivated reasoning

The previous results suggest that conservatism in belief revision does not simply follow people's cognitive difficulties when dealing with Bayes' rule. The greater likelihood of correct updating for those who support the reform is robust evidence that political views and identity shape belief formation. Indeed, the more people oppose the tax, the less likely they are to correctly update, as shown in columns (2-5) of Table 4.2. From columns (4-5), we also see that this result is entirely driven by the "pessimistic winners" : the updating of people who wrongly think that they will win does not depend on their approval, another indication that the revision in beliefs is driven by a rejection of the tax. This is not to say that few people seek to reach accurate beliefs. It still could be the case that informing any respondent that they would win makes them revise their subjective gain by, say, 100€ upwards, leading only those with small subjective losses to discover that they would win. One can actually see from the positive and statistically significant effect of *subjective gain (g)* that such an accuracy motive is at play. However, this effect remains small relative to those indicative of policy support, pointing out the importance of motivated reasoning. Column (3) further shows that the effect of approving the policy on correct updating is even stronger for more educated people—as the interaction term between approval and diploma is positive and significant—even capturing all the effect of initial tax approval.

The previous findings are comparable to empirical evidence from Kahan (2013) that politically motivated reasoning about climate change is not a reasoning deficiency but rather a reasoning adaptation following the interest that individuals have in conveying "their membership in and loyalty to affinity groups central to their personal well-being". In our case, the position relative to the Yellow Vests proxies for the groups that respondents identify with, and the differentiated updating along this spectrum can be interpreted as motivated reasoning. In addition, the hypothesis that motivated reasoning follows from a rational adaptation purpose can explain our finding that better educated people are *more* prone to motivated reasoning, as they are better able to formulate specious reasoning and reconcile antagonistic information and ideas. To the best of our knowledge, this result is the first evidence of rational motivated reasoning in the context of climate policies, complementing the findings of Druckman & McGrath (2019) that this mechanism can explain polarization around beliefs on climate change. [28]

28. This evidence provides empirical support for various models of endogenous belief formation. For example, Little (2019) formalizes the idea that directional motives may override accuracy motives and that people update auxiliary beliefs (in our case, the win/lose category) to preserve their consistency with core beliefs (here, rejection

TABLE 4.2 – Heterogeneity in updating.

	Correct updating (U)				
	(1)	(2)	(3)	(4)	(5)
Constant	0.120***	−0.036	−0.011	−0.073	0.707
	(0.012)	(0.190)	(0.192)	(0.192)	(1.007)
Winner, before feedback ($\dot{G}$)	0.695***	0.551***	0.563***		
	(0.078)	(0.083)	(0.083)		
Initial tax : PNR (I don't know)		0.179***	0.186***	0.199***	0.113
		(0.032)	(0.067)	(0.033)	(0.155)
Initial tax : Approves		0.176***	−0.031	0.216***	−0.162
		(0.046)	(0.115)	(0.049)	(0.185)
Diploma × Initial tax : PNR			−0.003		
			(0.025)		
Diploma × Initial tax : Approves			0.072**		
			(0.037)		
Subjective gain (g)		0.0004**	0.0004**	0.001***	−0.001
		(0.0002)	(0.0002)	(0.0003)	(0.004)
Subjective gain : unaffected ($g = 0$)		−0.127***	−0.126***	−0.208***	−0.331
		(0.033)	(0.033)	(0.033)	(0.219)
Bias about gain ($g - \hat{\gamma}$)		−0.00005	−0.0001	−0.001*	−0.0003
		(0.0001)	(0.0001)	(0.0003)	(0.0002)
Diploma (1 to 4)		0.014	0.009	−0.001	0.148*
		(0.013)	(0.014)	(0.013)	(0.078)
Retired		0.130*	0.127	0.108	0.124
		(0.079)	(0.079)	(0.080)	(0.435)
Active		0.166***	0.165***	0.160***	0.113
		(0.054)	(0.054)	(0.054)	(0.365)
Student		0.224***	0.229***	0.183**	0.402
		(0.075)	(0.075)	(0.074)	(0.526)
Yellow Vests : PNR		−0.045	−0.047	−0.031	0.013
		(0.047)	(0.047)	(0.048)	(0.246)
Yellow Vests : understands		−0.065*	−0.066*	−0.059*	0.141
		(0.034)	(0.034)	(0.034)	(0.170)
Yellow Vests : supports		−0.063*	−0.063*	−0.050	−0.156
		(0.036)	(0.036)	(0.036)	(0.206)
Yellow Vests : is part		−0.141*	−0.142*	−0.106	−0.985*
		(0.061)	(0.061)	(0.063)	(0.367)
Includes "pessimistic winners"	✓	✓	✓	✓	
Includes "optimistic losers"	✓	✓	✓		✓
Controls : socio-demo, politics, estimated gains		✓	✓	✓	✓
Observations	1,365	1,365	1,365	1,265	100
R^2	0.055	0.144	0.146	0.115	0.696

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Omitted variables are *Unemployed/Inactive* and *Yellow Vests : opposes*. The list of controls can be found in Appendix F.

Building upon the cognitive and social mechanisms described by Kraft et al. (2015) and documented by, e.g., Redlawsk (2002), we hypothesize the following narrative as one of the possible channels through which aversion to the carbon tax became entrenched. The Yellow Vests first gathered to defend their interest (above all their purchasing power), and a side effect of the daily interactions on roundabouts was to bring material and emotional support to the protesters (Challier, 2019). A group identity soon developed, which crystallized shared beliefs and affects such as a rejection of carbon taxation. This group identity gained support from a large majority of the population, notably through social networks. Now, due to the loyalty to the group and affects that have entered their subconscious, Yellow Vests supporters instinctively oppose any carbon tax and are prone to find excuses to cope with contradictory messages, e.g., by denying the reliability of these messages (Golman et al., 2016). Admittedly, such a narrative falls short of explaining the majority rejection among those who oppose the Yellow Vests (which may originate from pessimistic perceptions more than tax aversion), but it illustrates how pessimistic beliefs can be so persistent among Yellow Vests supporters.

Overall, these results show that people's pessimistic beliefs about the incidence of a tax & dividend are highly persistent. This pessimism is consistent with people forming their beliefs in a motivated way. Nevertheless, other mechanisms—such as a distrust of the government—may play a key role. Further research with a different design is needed to determine the relative importance of these different mechanisms.

of the tax). Admittedly, one might expect the importance of accuracy motives relative to directional motivated reasoning to increase in a higher stakes environment. However, this hypothesis cannot be tested in our setup, and previous literature does not provide conclusive evidence on the matter (Kunda, 1990; Camerer & Hogarth, 1999).

Table 4.3 – Effect of primings on beliefs about environmental effectiveness

	Environmental effectiveness			
	not "No"			"Yes"
	OLS		*logit*	*OLS*
	(1)	(2)	(3)	(4)
Info on Environmental Effectiveness (Z_E)	0.043**	0.063***	0.052***	0.059***
	(0.017)	(0.018)	(0.018)	(0.014)
Info on Climate Change (Z_{CC})	0.044*	0.041*	0.043*	0.029
	(0.024)	(0.024)	(0.024)	(0.018)
Info on Particulate Matter (Z_{PM})	0.039	0.029	0.037	0.017
	(0.024)	(0.024)	(0.024)	(0.019)
$Z_{CC} \times Z_{PM}$	−0.040	−0.033	−0.042	−0.005
	(0.035)	(0.034)	(0.033)	(0.027)
Controls : Socio-demo		✓	✓	✓
Observations	3,002	3,002	3,002	3,002
R^2	0.003	0.047		0.075

*p<0.1 ; **p<0.05 ; ***p<0.01

4.2 Environmental effectiveness

Table 4.3 reports the effect of displaying relevant information on the belief that our tax & dividend is environmentally effective. The effect of reporting a scientific consensus on environmental effectiveness (E) is positive and statistically significant, but its magnitude—approximately 5 p.p.—seems modest given that the question immediately follows the priming. The effects of information on climate change (CC) or particulates (PM) are smaller, and only CC is significant, which is understandable as the information is displayed at the very beginning of the survey and does not mention any environmental policy. As suggested by Millner & Ollivier (2016), given the complexity of the mechanisms at play, drawing a causal link between causes and consequences of environmental problems requires considerable cognitive effort, making it difficult to convince one of the effectiveness of policies that decentralize efforts to address pollution. Finally, we observe that our primings have no significant effect on beliefs about the causes and consequences of climate change. Overall, these primings appear insufficient to change most people's minds about climate change and carbon tax effectiveness.

4.3 Progressivity

Table 4.4 reveals the absence of an effect of explaining that our tax & dividend is progressive on perceived progressivity : the correlation between the two is close to 0 (at -0.006) and even has an unexpected negative sign. Column (2) of the same table clarifies why our treatment does not change the overall share of people who think that the policy is regressive : those who have a large bias in their perception of gains are in fact *more* prone to perceive *regressivity* once provided the information, by 13 p.p. This result may be a manifestation of the boomerang effect with people inclined to motivated reasoning, which has already been documented for Republican attitudes on climate change in the US (Zhou, 2016). Indeed, Hovland et al. (1953) showed that when someone is pressured to make a certain choice, psychological reactance (theorized by Brehm, 1966) can cause them to resist this pressure by adopting an opposite alternative. Although the effect on those without a large bias is not significant, providing them with information is associated with a lower perceived regressivity by 5 p.p. A possible explanation for the strong belief in regressivity is that people view the tax as regressive (relative to income) and the transfer as neutral (in absolute value) and mistakenly conclude that their combination is regressive. In any case, without a deep explanation of the underlying mechanisms, the progressivity of the policy remains unintuitive for most people, and we cannot convince them easily.

5 How beliefs determine attitudes

Our results clearly indicate that, at present, a carbon tax is unlikely to be accepted in France. However, we have also shown that people display overly pessimistic perceptions about the true effects of the policy. Most of them overestimate the negative impact on their purchasing power, think that the policy is regressive, and do not see it as environmentally effective. In this section, we examine to what extent the low acceptance rate reflects intrinsic preferences or incorrect perceptions. The question we address is whether convincing people about the actual incidence of the policy and its effectiveness would be sufficient to generate public support.

TABLE 4.4 – Effect of information on perceived progressivity

	Progressivity : not No (P)		
	(1)	(2)	(3)
Constant	0.419***	0.435***	0.052
	(0.022)	(0.033)	(0.319)
Information on progressivity (Z_P)	−0.021	0.050	0.051
	(0.027)	(0.040)	(0.041)
Large bias ($\lvert\widehat{\gamma} - g\rvert > 110$)		−0.028	−0.040
		(0.045)	(0.045)
Interaction $Z_P \times (\lvert\widehat{\gamma} - g\rvert > 110)$		−0.130**	−0.117**
		(0.055)	(0.055)
Controls : Socio-demo, politics			✓
Observations	1,444	1,444	1,444
R^2	0.0004	0.018	0.094

*p<0.1 ; **p<0.05 ; ***p<0.01

5.1 Self-interest

Identification challenge Among the three-quarters of the respondents expected to win from our tax & dividend, 62% both consider that they would not win and disapprove of the policy. We want to estimate to what extent knowing that they would win would lead them to approve of the reform. Because respondents thinking that they would win might differ in many respects from those thinking they would not, we cannot simply regress approval on perceptions of winning.

Main identification strategy To identify the effect *ceteris paribus* of self-interest on acceptance, we exploit exogenous variations in gains and losses. To do so, we consider a tax & targeted dividend, where respondents are randomly assigned to a compensation scheme for which they are eligible or not depending on their income (see Section 2.2.2). Formally, we denote by $I_{i,1}$ the income percentile of respondent's i and by $I_{i,2}$ that of the second adult in their household if there is one. We define the eligibility of adult $j \in \{1; 2\}$ as follows :[29]

$$T_{i,j} = \begin{cases} 0, & \text{if } I_{i,j} > t_i \\ 1, & \text{otherwise} \end{cases} \tag{5.1}$$

where $t_i \in \mathcal{T} = \{20; 30; 40; 50\}$ is the eligibility threshold randomly allocated to household i (see Section 2.2.2). As eligibility increases the likelihood—but does not necessarily imply—of belief that one wins from the policy, our method leads to a fuzzy RDD, where eligibility corresponds to the intention to treat and the respondents who believe that they will win correspond to the treated. Formally, we denote by G_i^T a dummy variable equal to 0 if respondent i thinks that they would lose from the tax & targeted dividend and 1 otherwise.

Similarly, A_i^T is a dummy variable equal to 0 if respondent i disapproves of this policy and 1 otherwise. We can then write the model as a two-stage least squares model with the following first-stage equation :

29. As explained in Section 2.2.2, we explicitly limit the number of beneficiaries to two per household.

$$G_i^T = \alpha_0 + \alpha_{T,1} T_{i,1} + \alpha_{T,2} T_{i,2} + \alpha_{T,3} \left(T_{i,1} \times T_{i,2} \right) + \sum_{k \in \mathcal{T}} \alpha_k \mathbb{1}_{t_i = k} + \alpha_S S_i + \alpha_{\mathbf{C}} \mathbf{C_i} + \alpha_{\mathbf{I}} \mathbf{I_i} + \eta_i \quad (5.2)$$

where $\mathbf{C_i}$ is a vector of respondent characteristics, S_i is a dummy variable equal to 1 when there is a single adult in the household, and $\mathbf{I_i}$ is a vector of income variables defined as $\left(I_{i,j},\ (\min(I_{i,j} - k,\ 0))_{k=20,70}\right)'_{j=1,2}$. $\mathbf{I_i}$ allows for a continuous piecewise linear relationship in incomes with slope changes at the 20th and 70th percentiles. Fixed effects for the policy assigned $\mathbb{1}_{t_i=k}$ ($k \in \mathcal{T}$) are also introduced to control for preferences regarding the specificities of the policy, i.e., the share of the population targeted by the policy and the value of the dividend. Finally, the second stage is written as follows :

$$A_i^T = \beta_0 + \beta_1 \widehat{G}_i^T + \sum_{k \in \mathcal{T}} \beta_k \mathbb{1}_{t_i = k} + \beta_S S_i + \beta_{\mathbf{C}} \mathbf{C_i} + \beta_{\mathbf{I}} \mathbf{I_i} + \epsilon_i \quad (5.3)$$

where $\widehat{G_i}^T$ denotes the fitted value of G_i^T from the first-stage regression. As seen from the first-stage results in Table 5.1, the eligibility of both respondents and households' second adults are positively correlated with beliefs about winning, so both instruments are relevant. The exclusion restriction states that conditional on income, being eligible affects approval solely through beliefs on winning. The RDD procedure employed in the first stage ensures that this is the case : conditional on income, eligibility is random, and by controlling for the specific policy assigned ($\mathbb{1}_{t_i=k}$), it should affect acceptance only through self-interest.

Alternative specifications for robustness To obtain more precise estimates, we include control variables in all specifications. In particular, we control for initial acceptance of our tax & dividend, as this should explain much of the variation in the dependent variable. In our main specification (1), we also exclude households where none of the adults has an income lying between the 10th and 60th percentiles to keep only those close enough to the thresholds. In specification (2), we replicate the same estimation using the full sample. In (3), we also compare our results with a simple OLS regression on the full sample. Finally, in (4), we exploit a methodology similar to the main specification—i.e., a fuzzy RDD—but applied to the customized feedback. Indeed, we use our estimation of respondents' net gains $\widehat{\gamma}$ as the assignment variable and the binary win/lose feedback $\widehat{\Gamma}$ as the intention to treat. As our feedback $\widehat{\Gamma}$ (which ranges from 0 to 1 at the threshold of zero net gain) is predictive of the belief about the win/lose category after feedback, G^F, we can determine the effect of this belief on acceptance, A^F. This alternative fuzzy RDD leads to the following two-stage least squares model :

$$G_i^F = \alpha_0 + \alpha_1 \widehat{\Gamma}_i + \alpha_{\gamma,1} \widehat{\gamma}_i + \alpha_{\gamma,2} \widehat{\gamma}_i^{\,2} + \alpha_{\mathbf{C}} \mathbf{C_i} + \alpha_{\mathbf{I}} \mathbf{I_i} + \eta_i \quad (5.4)$$

$$A_i^F = \beta_0 + \beta_1 \widehat{G}_i^F + \beta_{\gamma,1} \widehat{\gamma}_i + \beta_{\gamma,2} \widehat{\gamma}_i^{\,2} + \beta_{\mathbf{C}} \mathbf{C_i} + \beta_{\mathbf{I}} \mathbf{I_i} + \epsilon_i \quad (5.5)$$

where $\widehat{G}_i^F$ denotes the fitted value of G_i^F from the first-stage regression. The identification assumption of this second IV states that conditional on estimated net gains ($\widehat{\gamma}$)—which we control for with a quadratic specification—receiving win feedback ($\widehat{\Gamma} = 1$) affects approval solely through self-

TABLE 5.1 – First stage regressions results for self-interest

	Believes does not lose		
	Targeted Dividend (G^T) (1)	(2)	After feedback (G^F) (4)
Transfer to respondent (T_1)	0.199***	0.224***	
	(0.034)	(0.030)	
Transfer to spouse (T_2)	0.172***	0.156***	
	(0.042)	(0.039)	
$T_1 \times T_2$	−0.145***	−0.158***	
	(0.045)	(0.037)	
Simulated winner ($\widehat{\Gamma}$)			0.269***
			(0.058)
Initial tax Acceptance (A^0)	0.123***	0.154***	0.306***
	(0.041)	(0.033)	(0.066)
Controls : Incomes (piecewise continuous) estimated gains, socio-demo, other motives	✓	✓	✓
Controls : Policy assigned	✓	✓	
Sub-sample	[p10 ; p60]		$\lvert\widehat{\gamma}\rvert < 50$
Effective F-Statistic	15.6	23.8	21.3
Observations	1,969	3,002	757
R^2	0.221	0.196	0.301

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : In (1,2), the random eligibility to the dividend (conditionally on income) is used as source of exogenous variation in the belief. In (4), the discontinuity in the win/lose feedback when the net gain switches from negative to positive is used. Column numbers correspond to second stage results, Table 5.2 page suivante.

interest. We again restrict our analysis to respondents close enough to the threshold by retaining only those with net gains below 50€ per annum in absolute value ($|\widehat{\gamma}| < 50$).

Finally, we investigate alternative versions of the previous models in Appendix E. We estimate the effect of winning instead of not losing, and on approval instead of acceptance (Table E.1). We estimate our main specification with the slope in incomes changing at additional thresholds (30th, 40th, 50th or 60th percentile). Finally, we allow for heterogeneous effects along the income dimension (Table E.2).

Results The first-stage regression results are given in Table 5.1. The effective F-statistics (Olea & Pflueger, 2013) range from 15.6 to 23.8, indicating that both targeted transfers and feedback are strong instruments. Table 5.2 provides the second-stage results for the six main specifications, and additional specifications can be found in Appendix E. Overall, the estimated effects of self-interest indicate that believing that one would not lose increases acceptance by approximately 50 p.p. Both IV strategies yield consistent results, although they apply to different policies since revenue recycling is not designed in the same manner. The different results between the two local average treatment effects (LATE) (53 p.p. in column (1) vs. 64 p.p. in (4)) could also be due to the specificity of compliers in each setting. Since we have shown in Section 4.1 that respondents most likely to revise their beliefs after "win" feedback are less opposed to the tax, they may also be more inclined to accept the policy once they are convinced that they would win. Those most

TABLE 5.2 – Effect of self-interest on acceptance

	Acceptance ("Yes" or "Don't know" to policy support)			
	Targeted Dividend (A^T)			After Feedback (A^F)
	IV : random target/eligibility		*OLS*	*IV : discontinuity in feedback*
	(1)	(2)	(3)	(4)
Believes does not lose (G)	0.534***	0.476***	0.438***	0.644***
	(0.132)	(0.106)	(0.014)	(0.170)
Initial tax Acceptance (A^0)	0.356***	0.354***	0.361***	0.420***
	(0.041)	(0.034)	(0.026)	(0.074)
Controls : Incomes (piecewise continuous) estimated gains, socio-demo, other motives	✓	✓	✓	✓
Controls : Policy assigned	✓	✓	✓	
Sub-sample	[p10 ; p60]			$\lvert\hat{\gamma}\rvert < 50$
Effective F-Statistic	15.6	23.8		21.3
Observations	1,969	3,002	3,002	757
R^2	0.320	0.308	0.472	0.541

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. The list of controls can be found in Appendix F. The source of exogenous variation in the belief used in first-stages for the targeted dividend is the random assignment of the income threshold, which determines eligibility to the dividend. The first-stage for the non-targeted dividend exploits instead the discontinuity in the win/lose feedback when the net gain switches from negative to positive.

likely to comply in this setting could thus be more specific than those who comply when they are provided a (targeted) dividend that is large enough. The specificity of compliers could also explain why the average treatment effect estimated with the OLS is somewhat lower (44 p.p. in (3)), although the difference may also be due to a bias in the OLS that remains despite our powerful controls. The result of the OLS is also very close to that obtained from our main IV on the full sample (48 p.p. in (2)). The lower estimate found than in (1) could again be due to heterogeneous preferences between respondents depending on their income—with people at the bottom and top of the income distribution being less likely to revise their support when they learn that they would win—or from a less accurate identification when we enlarge the window and compare less similar respondents. Column (1) of Table E.2 in the Appendix confirms the existence of heterogeneous effects along the income distribution. Indeed, we find a larger effect for lower incomes, which may be due heterogeneous preferences or to the higher intensity of the treatment for low-income people (whose dividend represents a higher income share than the average).

Overall, these results show that convincing citizens' of the true incidence of a tax & dividend could substantially increase support for such a policy. Our results also qualify the findings of Anderson et al. (2019), who suggest that ideology better predicts carbon tax acceptance than self-interest. By distinguishing beliefs from preferences, we find that ideology plays an indirect role by shaping beliefs about one's self-interest and that beliefs directly affect acceptance.

5.2 Environmental effectiveness

Main identification strategy One of the strongest barriers to carbon tax implementation is a widespread perception of its environmental ineffectiveness. Our objective is therefore to assess to what extent learning about the environmental benefits of the tax could increase support. To identify this effect, we estimate a two-stage least squares (2SLS) model where the first stage uses random information to predict beliefs about environmental effectiveness, while the second stage regresses acceptance on the fitted exogenous variations in these beliefs. Because information on particulate matter (Z_{PM}) is poorly correlated with beliefs of effectiveness, we restrict the set of instruments to our primings on the scientific consensus (Z_E) and climate change (Z_{CC}). Although these primings do not have a very large effect on people's beliefs (as discussed in Section 4.2), these instruments are significantly related to our endogenous variable. Denoting by $\dot{A}^0$ the dummy for initial approval of the tax & dividend and by $\dot{E}$ the dummy for the belief that the policy is environmentally effective, we can write a 2SLS model as follows :

$$\dot{E}_i = \alpha_0 + \alpha_1 Z_{E,i} + \alpha_2 Z_{CC,i} + \alpha_{\mathbf{C}} \mathbf{C_i} + \eta_i \tag{5.1}$$

$$\dot{A}_i^0 = \beta_0 + \beta_1 \widehat{\dot{E}_i} + \beta_{\mathbf{C}} \mathbf{C_i} + \epsilon_i \tag{5.2}$$

where $\widehat{\dot{E}_i}$ denotes the fitted value of $\dot{E}_i$ from the first-stage regression and $\mathbf{C}$ is a vector of characteristics.

Alternative specifications for robustness checks Acknowledging that our priming could affect acceptance motives other than effectiveness alone, we include other motives in our list of control variables to avoid potential bias. In addition to the 2SLS (specification 1), we estimate an OLS (2) model to compare the LATE of our main specification with an ATE. For these two first specifications, we adopt strict definitions for our variables (i.e., the answer "Yes", denoted by a dot, to the belief in effectiveness and approval). Indeed, our instruments appear more effective in switching answers from "PNR" to "Yes" than from "No" to "PNR", hence greater statistical power with strict definitions. Specification (3) employs acceptance instead of approval as the dependent variable. In the Appendix, we also estimate a 2SLS with broad definitions only (i.e., the effect of a *not "No"* belief regarding effectiveness on acceptance of the policy), as well as two OLS regressions ("Yes" on acceptance and *not "No"* on acceptance). As a robustness check, we also report the results of a limited information maximum likelihood (LIML) estimation of our main results in the Appendix (Table E.3).

Results The first-stage regression results can be found in Table 5.3. Because of the relatively modest responses to our primings, the instruments are rather weak when broad definitions (i.e., *not "No"*) are taken in the first stage (effective F-statistic of 6), a problem that is alleviated in the case of strict definitions (11 in columns 1 and 3). Given the exogeneity of our instruments, the only concern is a potential bias towards OLS, which—as suggested by the results of column (2)—would entail estimates that are too conservative in our case. Table 5.4 reports the results of the second stages. They all consistently indicate a strong positive and significant effect of beliefs about environmental effectiveness on support for the policy. All else equal, believing that the tax is effective increases the likelihood of accepting it by 51 p.p. (3) and approving of it by 42 p.p. (1). The LATE is only slightly higher than the ATE estimated with OLS (2)—42 vs. 38 p.p. The lower

Table 5.3 – First stage regressions results for environmental effectiveness

	Environmental effectiveness	
	not "No" (1)	"Yes" (4,5)
Info on Environmental Effectiveness (Z_E)	0.062***	0.059***
	(0.017)	(0.014)
Info on Climate Change (Z_{CC})	0.030*	0.028**
	(0.017)	(0.013)
Controls : Socio-demo, other motives, incomes, estimated gains	✓	✓
Effective F-Statistic	6.0	11.2
Observations	3,002	3,002
R^2	0.121	0.123

*p<0.1 ; **p<0.05 ; ***p<0.01

Table 5.4 – Effect of believing in environmental effectiveness on approval

	Initial Tax & Dividend		
	Approval ($\dot{A}^0$)		Acceptance (A^0)
	IV	*OLS*	*IV*
	(1)	(2)	(3)
Believes in effectiveness ($\dot{E}$)	0.416**	0.374***	0.505**
	(0.168)	(0.013)	(0.242)
Instruments : info E.E. & C.C.	✓		✓
Controls : Socio-demo, other motives, incomes, estimated gains	✓	✓	✓
Effective F-Statistic	11.2		11.2
Observations	3,002	3,002	3,002
R^2	0.161	0.342	0.218

*p<0.1 ; **p<0.05 ; ***p<0.01

Note : Standard errors are reported in parentheses. The list of controls can be found in Appendix F, and first stage results in Table 5.3. The dependent variable corresponds to either initial approval (answer "Yes" to support of the policy) or acceptance (answer not "No"). The first stage exploits the information randomly displayed about climate change (C.C.) and the effectiveness of carbon taxation (E.E.) as exogenous instruments.

results obtained with OLS are more pronounced when using broad definitions for our variables, as seen in the Appendix (Table E.3). This discrepancy may be due to bias in the OLS or to the specificity of compliers : people who are most likely to change their mind following our information might also be more willing to accept the policy. Finally, we obtain identical results when running a 2SLS or an LIML for our main specification (1). For the strict definition of effectiveness, the LIML estimate (A2) is broadly consistent with the 2SLS result (3), though somewhat higher (64 p.p. vs. 51 p.p.).

5.3 Progressivity

As informing respondents does not convince them that our tax & dividend is progressive (see Section 4.3), we cannot perform an IV estimation to identify the causal effect of understanding the progressivity on support for the policy. In Appendix I, we estimate how one's belief in progressivity—interacted with other motives—correlates with acceptance using simple OLS and logit regressions. Controlling for many respondent characteristics and other motives for support, the effect of progressivity remains statistically significant and as high as 27 p.p. in our preferred specification. Of course, this result should be interpreted with caution since we can still suspect the results to be affected by unobserved confounders and reverse causality.

6 Conclusion

In this paper, we study how beliefs about a policy form and then determine attitudes towards it. We investigate this question through the study of carbon taxation in France during the Yellow Vests movement that started against fuel price increases. Our analysis is based on a new survey and official household survey data, enabling one to compare subjective beliefs with objective impacts on French households. We find that 70% disapprove of a carbon tax & dividend policy, which can be explained by pessimistic beliefs about its properties. Of our survey respondents, 89% overestimate its negative impact on their purchasing power, and most of them do not perceive it as environmentally effective or progressive. Pessimistic beliefs appear correlated with people's support for the scheme : the more they oppose the mechanism, the more pessimistic they are. Our results support a bidirectional causality between beliefs and attitudes towards the policy. People more opposed to the tax are more (pessimistically) biased in their treatment of *new* information with respect to it, indicating that beliefs about tax impacts are shaped by political identity. At the same time, we find that acceptance is causally determined by beliefs and that if people could be convinced about the incidence and effectiveness of a tax & dividend, this policy would likely be accepted by a majority, given the large effects of these motives (approximately 50 p.p. each).However, our treatments that provide accurate arguments in favor of the scheme mostly fail to convince people. The pessimism could be related to a strong distrust of the government, documented, e.g., in Alesina et al. (2018) and Algan et al. (2019), echoing recent findings that the ambition of climate policies increases with the level of trust (Rafaty, 2018). These results leave us with three main challenges. First, as it is unlikely that the issue of trust can be resolved in the short run, it seems necessary to find climate policies that would be accepted by a majority. We address this question in a companion paper (Douenne & Fabre, 2020a), in which we assess both knowledge and beliefs about climate change and the preferred policies of French people. Second, as trust in government needs to be restored in the longer run, it is crucial to analyze what causes distrust and how it can be overcome. Third, it is important to assess to what extent the mechanisms of belief formation and their effects on political attitudes we document can be generalized to other policies and other contexts. Although rejection of the tax may be lower in a different country, biases in perceptions and political polarization may occur everywhere. Thus, a lesson must be learned for policy design and implementation to avoid another carbon tax debacle *à la Française*. Indeed, our results suggest that popular opposition to a poorly designed carbon tax may well jeopardize the acceptability of any new version of the tax.

Appendix

A Raw data

Table A.1 – Sample characteristics : quotas.

	Population	Sample
gender		
woman	*0.52*	0.53
man	*0.48*	0.47
age		
18-24	*0.12*	0.11
25-34	*0.15*	0.11
35-49	*0.24*	0.24
50-64	*0.24*	0.26
>65	*0.25*	0.27
profession		
farmer	*0.01*	0.01
independent	*0.03*	0.04
executive	*0.09*	0.09
intermediate	*0.14*	0.14
employee	*0.15*	0.16
worker	*0.12*	0.13
retired	*0.33*	0.33
inactive	*0.12*	0.11
education		
No diploma or *Brevet*	*0.30*	0.24
CAP or *BEP*	*0.25*	0.26
Bac	*0.17*	0.18
Higher	*0.29*	0.31
size of town		
rural	*0.22*	0.24
<20k	*0.17*	0.18
20-99k	*0.14*	0.13
>100k	*0.31*	0.29
Paris area	*0.16*	0.15
region		
IDF	*0.19*	0.17
Nord	*0.09*	0.10
Est	*0.13*	0.12
SO	*0.09*	0.09
Centre	*0.10*	0.12
Ouest	*0.10*	0.10
Occ	*0.09*	0.08
ARA	*0.12*	0.13
PACA	*0.09*	0.08

Table A.2 – Households' characteristics.

	Population	Sample
Household composition (mean)		
Household size	*2.36*	2.38
Number of adults	*2.03*	1.93
c.u.	*1.60*	1.61
Energy source (share)		
Gas	*0.42*	0.36
Heating oil	*0.12*	0.09
Accommodation surface (m^2)		
mean	*97*	96
p25	*69*	66
p50	*90*	90
p75	*120*	115
Distance travelled by car (km/year)		
mean	*13,735*	15,328
p25	*4,000*	4,000
p50	*10,899*	10,000
p75	*20,000*	20,000
Fuel economy (L/100 km)		
mean	*6.39*	7.18
p25	*6*	5
p50	*6.5*	6
p75	*7.5*	7

B Notations

To improve the understanding of our specifications in the regression tables, we adopt consistent notations throughout the paper. For questions where possible answers are "Yes"/"No"/"PNR", we define two kinds of dummy variables : the default ones correspond to *not "No"* answers, while we place a dot on dummy variables for *"Yes"*. For example, acceptance is denoted by A, while approval is denoted by $\dot{A}$. Furthermore, for questions that are asked several times, namely, acceptance and win/lose category, an exponent is added to specify the step at which the question is asked. Table B.1 describes these exponents and the notations corresponding to the different notions of gain that we use. Uppercase is used for binary and lowercase for continuous variables, and Greek letters denote objective notions, with a hat for our estimation of gains and without for the true (unknown) ones. To provide another example, the broad notion of self-interest at the initial step, i.e., the belief that one does not lose, is denoted by G^0, and the strict belief that one wins at tax & targeted dividend is denoted by $\dot{G^T}$.

TABLE B.1 – Notations for the different reforms and for gain notions.

Step	Initial	After knowledge : *1*		with Targeting
Variants	–	Progressivity	Feedback	–
Exponent	*0*	*P*	*F*	*T*

Gain	Subjective	True	Estimated
Numeric	g	γ	$\widehat{\gamma}$
Binary	$\dot{G}$ $(g > 0)$, G $(g \geq 0)$	Γ	$\widehat{\Gamma}$

C The use of official household survey data

The paper employs official survey data for two purposes : (i) computing the distribution of increases in fossil fuel expenditures and (ii) predicting the expected net gain of each respondent based on their energy characteristics. Section C.1 presents the three official surveys from Insee (the French national statistics bureau) that are used. Section C.2 details the formulas needed to compute the value of the dividend and households' expected net gains from their expenditures. Section C.3 explains how by using two distinct surveys, we can obtain a simple formula to predict respondents' net gain simply based on their energy characteristics and then test out-of-sample the likelihood of making a correct prediction.

C.1 Official household surveys from Insee

Consumer survey "Budget de Famille" The consumer survey (BdF 2011) is a household survey providing information on all households' revenues and expenditures, together with many socio-demographic characteristics. It was conducted in several waves from October 2010 to September 2011 on a representative sample of 10,342 French households. The main advantage of BdF when studying the incidence of carbon taxation is that expenditures on both housing and transportation energy are reported. Consumption of housing energy is taken from households' bills, and for most other goods, respondents report their expenditures over the past week. However, as explained in Douenne (2020), this data collection is problematic when examining the incidence of a tax on transportation energy, as short-run fluctuations in consumption lead to overestimation of the heterogeneity in expenditures.

Transport survey "Enquête Nationale Transports et Déplacements" To overcome this limitation, BdF is matched with the transport survey (ENTD 2008). ENTD was conducted in several waves from April 2007 to April 2008 on a representative sample of 20,178 French households. It provides information on household characteristics, vehicle fleets and use over the past week, but most important, it provides information on annual distances travelled with these vehicles. This last information enables us to recover the distribution of transport fuel expenditures without overestimating its spread. Such matching is not necessary for housing energy, as it already represents consumption over long periods in BdF.

Housing survey "Enquête Logement" The housing survey (EL 2013) was conducted between June 2013 and June 2014 on a sample of 27,137 households in metropolitan France. It includes considerable information on households' characteristics, as well as their housing energy bills. The distribution of energy expenditures is very close to that of BdF.

C.2 Formulas to compute monetary effects of carbon tax policy

To compute the monetary impact of a carbon tax increase on household h, we decompose current energy expenditures $E_h(\tau)$ as a product of current price $P(\tau)$ and current quantities consumed $Q_h(\tau)$, each being a function of the excise tax τ of which the carbon tax is apart : [30]

$$E_h(\tau) = P(\tau) Q_h(\tau)$$

Small variations in expenditures can then be expressed as :

$$\frac{dE}{E}(\tau) = \frac{dP}{P}(\tau) + \frac{dQ}{Q}(\tau)$$

The variation in quantities can be rewritten as a function of the price variation :

$$\frac{dQ}{Q}(\tau) = e\frac{dP}{P}(\tau)$$

where $e = \frac{dQ_h}{dP} \cdot \frac{P}{Q_h}$ is the price elasticity of the energetic good considered, which is assumed to be constant and identical across households. For all energy types, the final price can itself be decomposed as :

$$P(\tau) = (p + i\tau)(1 + t)$$

where t is the value added tax (VAT) rate (assumed constant) that applies after excise taxes, i is the incidence of excise taxes on consumers (assumed constant), and $p + (i-1)\tau$ is the producer price as a function of τ. [31] When the carbon price changes so that the excise taxes vary from τ to

30. The French carbon tax "Contribution Climat Energie" is a component of existing taxes on energetic products : TICPE for transport and heating oils, TICGN for natural gas.

31. Hence, p is the producer price when $\tau = 0$.

some level τ', we therefore have :

$$\frac{\Delta P(\tau)}{P} = \frac{P(\tau') - P(\tau)}{P(\tau)} = \frac{(p + i\tau')(1+t) - (p + i\tau)(1+t)}{(p + i\tau)(1+t)} = \frac{i(\tau' - \tau)}{p + i\tau}$$

Thus, by carrying on the first-order approximation, one can express an increase in expenditures associated with a carbon price increase as :

$$\Delta E_h(\tau) = E_h(\tau)(1+e)\frac{\Delta P}{P} = E_h(\tau)(1+e)\frac{i(\tau' - \tau)}{p + i\tau} \tag{C.1}$$

We can replicate similar calculations to obtain the expected variations in tax paid on energy by household h, ΔT_h. Starting from the expression for T_h—which is the sum of excise taxes and the VAT on the energy good—we have :

$$T_h(\tau) = Q_h(\tau)\Big((1+t)\tau + t\big(p + (i-1)\tau\big)\Big)$$

from which we obtain :

$$\Delta T_h(\tau) = Q_h(\tau)\left(1 + e\frac{i(\tau' - \tau)}{p + i\tau}\right)\Big(t\big(p+(i-1)\tau'\big)+(1+t)\tau'\Big) - Q(\tau)\Big(t\big(p+(i-1)\tau\big)+(1+t)\tau\Big) \tag{C.2}$$

Finally, the net gain of a household h from a tax & dividend is written as follows :

$$\gamma_h(\tau) = N_h^a \cdot \frac{\sum_h \Delta T_h(\tau)}{N^a} - \Delta E_h^{transport}(\tau) - \Delta E_h^{housing}(\tau) \tag{C.3}$$

where γ_h denotes its net gain from the policy, N_h^a is the number of adults receiving the dividend in this household, N^a is the total number of adults receiving it, and $\Delta E_h^{transport}$ (resp. $\Delta E_h^{housing}$) is the increase in their expenditures on transport (resp. housing) energy. From households' energy expenditures and making assumptions on elasticities and tax incidence, equations (C.1) to (C.3) enable us to obtain the value of dividends and the impact of the policy on households' purchasing power. We use equation (C.3) to estimate the biases and objective distribution of net gains in Section 3 and the customized feedback in Section 4.

When asked to estimate the impact of the policy on their own purchasing power, respondents simply had to make an estimation over :

$$\Delta E_h(\tau) = E_h(\tau)(1+e)\frac{\Delta P}{P}$$

where for simplicity, ΔP was given for transport fuels, and $\frac{\Delta P}{P}$ was given for housing energy. Thus, they were not required to make any specific assumption about existing taxes or tax incidence but simply to estimate their consumption and price elasticity.

C.3 Predicting gains and losses

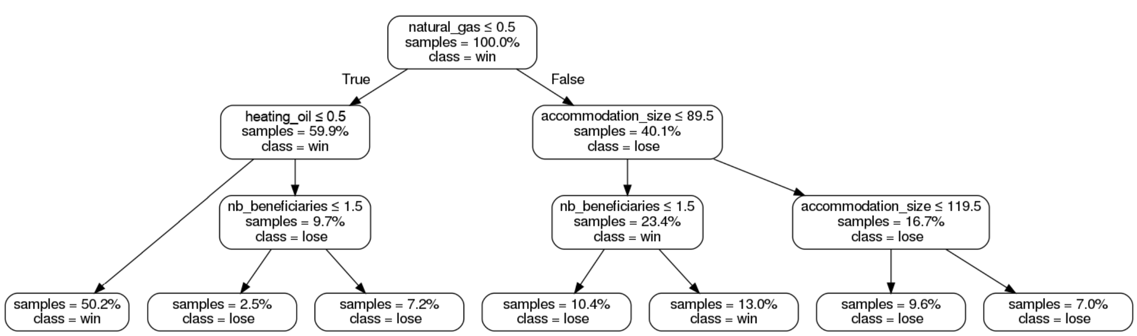
As explained in Section 2.3, to estimate respondents' bias and provide customized feedback on their win/lose category, we need to estimate their increase in housing energy expenditures, $\Delta E_h^{housing}$, based on their energy characteristics.

To do so, we regress $\Delta E_h^{housing}$ on households' characteristics using the housing survey. Table C.1 presents several specifications of this regression, and its last row shows the out-of-sample error rate, computed with the consumer survey. All specifications yield a similar error rate of 15-17%. Given the concern that respondents could make mistakes when reporting the accommodation size in the entry field, we used the first specification in our survey, as it does not rely as heavily as the others on the accommodation size. To balance the error rates for losing households that are mistakenly estimated to be winners and for winners who are mistakenly estimated to be losers, we add a constant of 16.1 in our estimation of yearly net gain, which is thus the sum of 16.1 plus 110 times one or two (depending on the number of adults) minus increases in transport and housing energy expenditures. We selected OLS as our prediction method for the estimation of net gain because it compares well with respect to alternative methods. We also classified winners and losers using a decision tree and obtained a very close error rate : 17.4% (see Figure C.1). Finally, statistical matching provided an error rate of 17.7%.

TABLE C.1 – Determinants of housing energy expenditures.

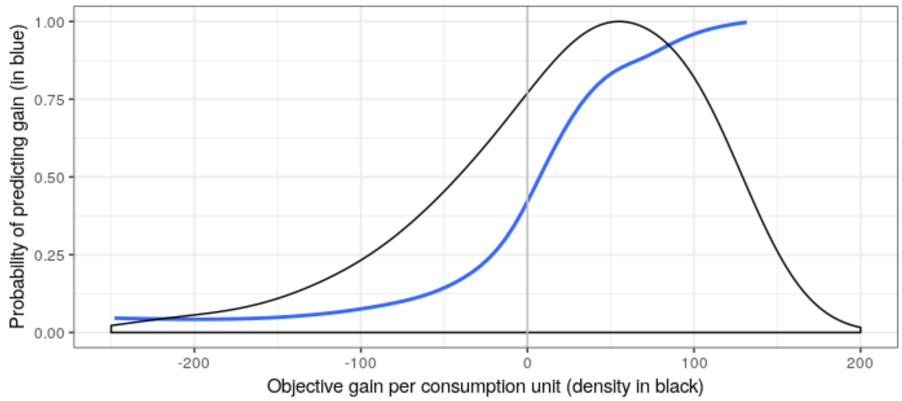
	Increase in housing energy expenditures (€/year)		
	(1)	(2)	(3)
Constant	−55.51***		−0.634
	(1.237)		(1.489)
Housing energy : Gas	124.6***		1.173
	(1.037)		(2.323)
Housing energy : Heating oil	221.1***	129.8***	130.4***
	(1.719)	(3.752)	(4.002)
Accommodation size (m^2)	0.652***		0.024
	(0.012)		(0.015)
Accommodation size × Gas		1.425***	1.397***
		(0.007)	(0.024)
Accommodation size × Heating oil		0.945***	0.922***
		(0.029)	(0.032)
Observations	26,729	26,729	26,729
R^2	0.545	0.716	0.599
Error rate	0.166	0.155	0.155

*p<0.1 ; **p<0.05 ; ***p<0.01



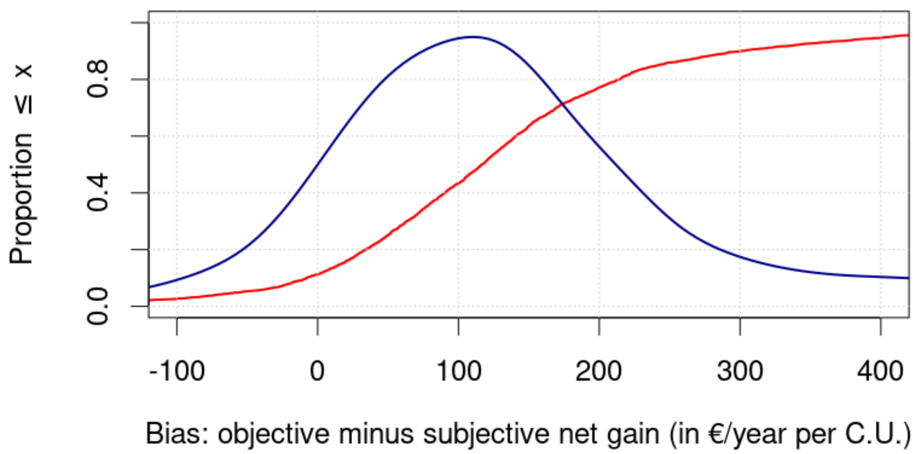
NOTE : This figure reads : the 50.2% of respondents who do not use natural gas nor heating oil (≤ 0.5) as their heating source are predicted to win from the Tax & Dividend.

FIGURE C.1 – Decision tree that classifies households between winners and losers.



NOTE : The black curve corresponds to the density of households' objective net gains in the consumer survey. As shown by the blue curve, households in the consumer survey who would gain 100€ per C.U. —as directly computed from their energy bills— were predicted to be winner —from their energy characteristics— in 96% of cases. See discussion in the main text, Section 4.1.1 page 124.

FIGURE C.2 – Probability that our net gains' estimation correctly predicts the win/lose category.



NOTE : The red curve indicates for 11% of respondents, objective gains are lower than subjective ones, while for 23% of them they are higher by at least 200€. The blue curve indicates that the most common bias is an underestimation of gains by about 100€. See discussion in the main text, Section 3.1 page 119.

FIGURE C.3 – CDF (in red) and PDF (in blue) of the bias.

D Persistence of beliefs in self-interest

TABLE D.1 – Transition matrix after telling respondents they are expected to *win* (75.8%).

Before \ After	**Winner** (25%)	**Unaffected** (28%)	**Loser** (47%)
Winner (16%)	79%	13%	8%
Unaffected (24%)	22%	63%	15%
Loser (60%)	12%	18%	70%

TABLE D.2 – Transition matrix after telling respondents they are expected to *lose* (24.2%).

Before \ After	**Winner** (3%)	**Unaffected** (12%)	**Loser** (86%)
Winner (7%)	16%	3%	81%
Unaffected (15%)	5%	50%	46%
Loser (78%)	1%	5%	94%

TABLE D.3 – Share who align their beliefs with feedback, among those with large gain or loss ($|\widehat{\gamma}| > 110$).

	Aligned with feedback : $G^F = \widehat{\Gamma}$	
	$\widehat{\Gamma} = 1$ (81.6%)	$\widehat{\Gamma} = 0$ (18.4%)
Initial belief winner ($g > 0$) (19.4%)	77.6% [68.5%; 84.7%]	78.4% [43.2%; 94.5%]
Initial belief unaffected ($g = 0$) (28.2%)	20.7% [14.8%; 28.1%]	32.7% [14.7%; 57.7%]
Initial belief loser ($g < 0$) (52.3%)	10.8% [7.3%; 15.8%]	92.2% [84.5%; 96.3%]
Initial belief affected ($g \neq 0$) (70.8%)	32.7% [27.7%; 38.1%]	91.1% [83.5%; 95.4%]
All (100%)	28.9% [24.8%; 33.3%]	83.0% [74.8%; 88.9%]

NOTE : The 95% confidence intervals for binomial probabilities are given in brackets.

E Additional specifications

Table E.1 – Effect of self-interest on acceptance : second stages of alternative specifications

	Targeted Dividend (A^T)			After Feedback (A^F)		
	Acceptance	Approval		Acceptance	Approval	
	(1)	(2)	(3)	(4)	(5)	(6)
Believes wins	0.574***	0.357***		1.131***	0.609***	
	(0.136)	(0.117)		(0.298)	(0.233)	
Believes does not lose			0.343***			0.347***
			(0.113)			(0.133)
Controls : Incomes (piecewise continuous) estimated gains, socio-demo, other motives	✓	✓	✓	✓	✓	✓
Controls : Policy assigned	✓	✓	✓			
Sub-sample : [p10 ; p60] (A^T) or $\lvert\widehat{\gamma}\rvert < 50$ (A^F)	✓	✓	✓	✓	✓	✓
Effective F-Statistic	21.3	21.3	15.6	11.4	11.4	21.3
Observations	1,969	1,969	1,969	757	757	757
R^2	0.321	0.217	0.217	0.541	0.518	0.518

*p<0.1 ; **p<0.05 ; ***p<0.01

Note : See results of main specifications, Table 5.2 page 134. As in the latter Table, the source of exogenous variation in the belief used in first-stages for the targeted dividend is the random assignment of the income threshold, which determines eligibility to the dividend. The first-stage for the non-targeted dividend exploits instead the discontinuity in the win/lose feedback when the net gain switches from negative to positive.

TABLE E.2 – Effect of self-interest on acceptance : the role of incomes

	Acceptance of Tax & Targeted Dividend (A^T)				
	(1)	(2)	(3)	(4)	(5)
Believes does not lose (G^T)	0.773***	0.556***	0.549***	0.535***	0.502***
	(0.222)	(0.133)	(0.133)	(0.133)	(0.130)
Income above 35th percentile ($\mathbb{1}_{I>p35}$)	0.343				
	(0.508)				
$G^T \times \mathbb{1}_{I>p35}$	−0.392				
	(0.311)				
Initial tax Acceptance (A^0)	0.387***	0.353***	0.354***	0.356***	0.359***
	(0.058)	(0.041)	(0.041)	(0.041)	(0.040)
Percentile with additional income slope change		30	40	50	60
Controls : Incomes (piecewise continuous) estimated gains, socio-demo, other motives	✓	✓	✓	✓	✓
Sub-sample : [p10 ; p60] ; Controls : Policy assigned	✓	✓	✓	✓	✓
Effective F-Statistic	5.5	15.3	15.2	15.2	16.1
Observations	1,969	1,969	1,969	1,969	1,969
R^2	0.571	0.321	0.321	0.321	0.321

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : See results of main specifications, Table 5.2 page 134. The source of exogenous variation in the belief used in the first-stage is the random assignment of the income threshold, which determines eligibility to the dividend.

TABLE E.3 – Effect of believing in environmental effectiveness on support : second stages of alternative specifications

	Initial Tax & Dividend				
	Approval ($\dot{A}^0$)		Acceptance (A^0)		
	logit	*LIML*	*OLS*	*IV*	*OLS*
	(A1)	(A2)	(A3)	(A4)	(A5)
Environmental effectiveness : “Yes”	0.293***	0.643***	0.367***		
	(0.021)	(0.320)	(0.020)		
Environmental effectiveness : not “No”				0.479**	0.413***
				(0.230)	(0.015)
Instruments : info E.E. & C.C.		✓		✓	
Controls : Socio-demo, other motives	✓	✓	✓	✓	✓
Effective F-Statistic				6.0	
Observations	3,002	3,002	3,002	3,002	3,002
R^2		0.295	0.295	0.218	0.379

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. For logit, average marginal effects are reported and not coefficients. The list of controls can be found in Appendix F, and the main results in Table 5.4 page 136. As in the latter Table, the dependent variable corresponds to either initial approval (answer “Yes” to support of the policy) or acceptance (answer not “No”). The first stage exploits the information randomly displayed about climate change (C.C.) and the effectiveness of carbon taxation (E.E.) as exogenous instruments.

F Control variables

Socio-demo : *respondent's income, household's income, sex, age* (5 categories)*, employment status* (9 categories)*, socio-professional category* (8 categories)*, region of France* (10 categories)*, size of town* (5 categories)*, diploma* 4 categories*, household size, number of people above 14, number of adults, number of c.u., income per c.u., smokes, favored media for news* (5 categories).

Politics : *extreme left, left, center, right, extreme right, interest in politics* (3 categories)*, conservative, liberal, humanist, patriot, environmentalist, apolitical.*

Political leaning : *extreme left, left, center, right, extreme right, indeterminate.*

Energy : *heating mode* (collective vs. individual)*, heating energy* (7 categories)*, annual distance travelled, fuel economy, diesel* (binary)*, gasoline* (binary)*, number of vehicles.*

Incomes : *income of respondent, income of the second adult, income of respondent squared, income of the second adult squared, dummy for absence of second adult.*

Incomes (piecewise continuous) : *income percentile of respondent (I_1), income percentile of the second adult (I_2), dummy for absence of second adult,* $\min(I_1 - 20, 0)$, $\min(I_1 - 70, 0)$, $\min(I_2 - 20, 0)$, $\min(I_2 - 70, 0)$.

Estimated gains : *simulated net gain, squared simulated gain.*

G Questionnaire

Priming

1. [No priming] Welcome to this survey.
   It was conceived by two researchers in social science. It lasts about 15-20 minutes.
2. [Info PM] Welcome to this survey.
   It was conceived by two researchers in social science. It lasts about 15-20 minutes.

   Before starting, please read carefully the information below on particulate matter pollution :

   — particulate matter are responsible for 48,000 deaths in France each year ;

   — particulate matter reduce the life expectancy of French people by 9 months ;

   — reducing fuel consumption would reduce the health problems associated with particulate matter.

   Source : France Public Health Report (2016)
3. [Info CC] Welcome to this survey.
   It was conceived by two researchers in social science. It lasts about 15-20 minutes.

Please read carefully the information below on climate change.

- Climate change is already responsible for 150,000 deaths annually.
- If greenhouse gas emissions continue on their current trend, the average global warming will be +5°C in 2100 and +8°C in 2250.
- A rapid transition to renewable energies is technically possible and would contain global warming at +2°C.

According to scientists, in the absence of ambitious measures :

- a large proportion of species face an increased risk of extinction ;
- natural disasters will intensify (hurricanes, heat waves, droughts, floods, forest fires, etc.) ;
- by 2100, 270 million more people would be flooded each year due to sea-level rise ;
- violent conflicts and migration flows can be expected to increase.

Sources : Burke et al (2009), Hinkel et al (2014), IPCC Report (2014), Meinshausen et al (2011), Patz et al (2005)

Socio-demographics

4. What is your postal code ?
5. What is your gender (in the sense of civil status) ?
   Female ; Male
6. What is your age group ?
   18 to 24 years old ; 25 to 34 years old ; 35 to 49 years old ; 50 to 64 years old ; 65 years old or more
7. What is your employment status ?
   Permanent ; Temporary contract ; Unemployed ; Student ; Retired ; Other active ; Inactive
8. What is your socio-professional category ? (Remember that the unemployed are active workers).
   Farmer ; Craftsperson, merchant ; Independent ; Executive ; Intermediate occupation ; Employee ; Worker ; Retired ; Other Inactive
9. What is your highest degree ?
   No diploma ; Brevet des collèges ; CAP or BEP [secondary] ; Baccalaureate ; Bac +2 (BTS, DUT, DEUG, schools of health and social training...) ; Bac +3 (licence...) [bachelor] ; Bac +5 or more (master, engineering or business school, doctorate, medicine, master, DEA, DESS...)
10. How many people live in your household ? Household includes : you, your family members who live with you, and your dependents.
11. What is your net **monthly** income (in euros) ? **All income** (before withholding tax) is included here : salaries, pensions, allowances, APL [housing allowance], land income, etc.
12. What is the net **monthly** income (in euros) **of your household** ? **All income** (before withholding tax) is included here : salaries, pensions, allowances, APL [housing allowance], land income, etc.
13. In your household how many people are 14 years old or older (**including yourself**) ?
14. In your household, how many people are over the age of majority (**including yourself**) ?

Energy characteristics

15. What is the surface area of your home ? (in m²)
16. What is the heating system in your home ?
    Individual heating ; Collective heating ; PNR (Don't know, don't say)
17. What is the main heating energy source in your home ?
    Electricity Town gas ; Butane, propane, tank gas ; Heating oil ; Wood, solar, geothermal, aerothermal (heat pump) ; Other ; PNR (Don't know, don't say)
18. How many motor vehicles does your household have ?
    None ; One ; Two or more
19. [Without a vehicle] How many kilometers have you driven in the last 12 months ?
20. [One vehicle] What type of fuel do you use for this vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
21. [One vehicle] What is the average fuel economy of your vehicle ? (in Liters per 100 km)
22. [One vehicle] How many kilometers have you driven with your vehicle in the last 12 months ?
23. [At least two vehicles] What type of fuel do you use for your main vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
24. [At least two vehicles] What type of fuel do you use for your second vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
25. [At least two vehicles] What is the average fuel economy of all your vehicles ? (in Liters per 100 km)
26. [At least two vehicles] How many kilometers have you driven with all your vehicles in the last 12 months ?

Partial reforms [transport / housing]

27. Do you think that an increase in VAT would result in a loss of more purchasing power for your household than for the average French household ?
    Yes, much more ; Yes, a little more ; As much as the average ; No, a little less ; No, a lot less ; PNR (Don't know, don't say)
28. Do you think that an increase in [fuel taxes / taxes on gas and heating oil] would cause your household to lose more purchasing power than an average French household ?
    Yes, much more ; Yes, a little more ; As much as the average ; No, a little less ; No, a lot less ; PNR (Don't know, don't say)
29. The government is studying a fuel tax increase, whose revenues would be redistributed to all households, regardless of their income. This would imply :
    — [an increase in the price of gasoline by 11 cents per liter and diesel by 13 cents per liter / a 13% increase in the price of gas, and a 15% increase in the price of heating oil] ;
    — an annual payment of [60 / 50]€ to each adult, or [120 / 100]€ per year for a couple.

    In terms of purchasing power, would your household win or lose with such a measure ?
    Win ; Be unaffected ; Lose

30. [*Winner* selected] **According to you, your household's purchasing power would increase :**
From 0 to [10·uc] € per year ; From [10·uc] to [20·uc] € per year ; From [20·uc] to [30·uc] € per year ; From [30·uc] to [40·uc] € per year ; More than [40·uc] € per year
31. [*Loser* selected] **According to you, the purchasing power of your household would decrease :**
From 0 to [15·uc] € per year ; From [15·uc] to [40·uc] € per year ; From [40·uc] to [70·uc] € per year ; From [70·uc] to [110·uc] € per year ; From [110·uc] to [160·uc] € per year ; From more than [160·uc] € per year
32. If fuel prices increased by 50 cents per liter, by how much would **your household** reduce its fuel consumption ?
0% - [*I already consume almost none / I am already not consuming*] *; 0%* - [*I am constrained on all my trips / I will not reduce it*] *; From 0% to 10% ; From 10% to 20% ; From 20% to 30% ; More than 30%* - [*I would change my travel habits significantly / I would change my consumption significantly*]
33. In your opinion, if [fuel prices increased by 50 cents per liter / gas and heating oil prices increased by 30%], by how much would **French people** reduce their consumption on average ?
From 0% to 3% ; From 3% to 10% ; From 3% to 10% ; From 10% to 20% ; From 20% to 30% ; More than 30%
34. Do you think that an increase in taxes on gas and heating oil would cause your household to lose more purchasing power than the average French household ?
Yes, a lot more ; Yes, a little more ; As much as average ; No, a little less ; No, a lot less ; PNR (Don't know, don't say)

Tax & dividend : initial

35. The government is studying an increase in the carbon tax, whose revenues would be redistributed to all households, regardless of their income. This would imply :
    - an increase in the price of gasoline by 11 cents per liter and diesel by 13 cents per liter ;
    - an increase of 13% in the price of gas, and 15% in the price of heating oil ;
    - an annual payment of 110€ to each adult, or 220€ per year for a couple.

    In terms of purchasing power, would your household win or loser with such a measure ?
    Win ; Be unaffected ; Lose
36. [*Winner* selected] **According to you, your household's purchasing power would increase :**
From 0 to [20·uc] € per year ; From [20·uc] to [40·uc] € per year ; From [40·uc] to [60·uc] € per year ; From [60·uc] to [80·uc] € per year ; From more than [80·uc] € per year
37. [*Loser* selected] **According to you, the purchasing power of your household would decrease :**
From 0 to [30·uc] € per year ; From [30·uc] to [70·uc] € per year ; From [70·uc] to [120·uc] € per year ; From [120·uc] to [190·uc] € per year ; From [190·uc] to [280·uc] € per year ; From more than [280·uc] € per year

38. [[empty] / Scientists agree that a carbon tax would be effective in reducing pollution.] Do you think that such a measure would reduce pollution and fight climate change ?
Yes ; No ; PNR (Don't know, don't say)
39. In your opinion, which categories would lose [[blank] / purchasing power] with such a measure ? (Several answers possible)
No one ; The poorest ; The middle classes ; The richest ; All French people ; Rural or peri-urban people ; Some French people, but not a particular income category ; PNR (Don't know, don't say)
40. In your opinion, what categories would gain purchasing power with such a measure ? (Several answers possible)
No one ; The poorest ; The middle classes ; The richest ; All French people ; Urban dwellers ; Some French people, but not a particular income category ; PNR (Don't know, don't say)
41. Would you approve of such a measure ?
Yes ; No ; PNR (Don't know, don't say)

Tax & dividend : after knowledge

42. [Feedback] We always consider the same measure. As a reminder, it would imply :
    - an increase in the price of petrol by 11 cents per liter and diesel by 13 cents per liter ;
    - an increase of 13% in the price of gas, and 15% in the price of heating oil ;
    - an annual payment of 110€ to each adult, or 220€ per year for a couple.

In five out of six cases, a household with the same characteristics as yours would **[win / lose]**. (The characteristics taken into account are : heating with [source] for a dwelling of [size] m^2 ; [distance] km covered with an average consumption of [fuel economy] liters per 100 km).

Based on this estimate, do you now think that your household would be :
Winner ; Unaffected ; Loser

43. [Info on progressivity] On average, this measure would increase the purchasing power of the poorest households, and decrease that of the richest, who consume more energy.

    In view of this new information, do you think this measure would benefit the poorest ?
    Yes ; No ; PNR (Don't know, don't say)
44. [No info on progressivity] Do you think this measure would benefit the poorest ?
Yes ; No ; PNR (Don't know, don't say)
45. In view of the above estimate, would you approve of such a measure ?
Yes ; No ; PNR (Don't know, don't say)
46. Why do you think this measure is beneficial ? (Maximum three responses)
Contributes to the fight climate change ; Reduces the harmful effects of pollution on health ; Reduces traffic congestion ; Increases my purchasing power ; Increases the purchasing power of the poorest ; Fosters France's independence from fossil energy imports ; Prepares the economy for tomorrow's challenges ; For none of these reasons ; Other (specify) :
47. Why do you think this measure is unwanted ? (Maximum three answers)
Is ineffective in reducing pollution ; Alternatives are insufficient or too expensive ; Penalizes rural areas ; Decreases my purchasing power ; Decreases the purchasing power of some modest

households ; Harms the economy and employment ; Is a pretext for raising taxes ; For none of these reasons ; Other (specify) :

Tax & targeted dividend

48. The government is studying an increase in the carbon tax, whose revenues would be redistributed **to the [20 / 30 / 40 / 50]% of the poorest French people only**. This would imply :
    - an increase in the price of gasoline by 11 cents per liter and diesel by 13 cents per liter ;
    - an increase of 13% in the price of gas, and 15% in the price of heating oil ;
    - an annual payment of [550 / 360 / 270 / 220]€ for each adult earning less than [780 / 1140 / 1430 / 1670]€ per month (welfare benefits included, before withholding tax) ;
    - no compensation for the others.

We estimate that in your household, [number of recipients] persons would receive this payment.

In terms of purchasing power, would your household win or lose with such a measure ?
Win ; Be unaffected ; Lose

49. Would you approve such a measure ?
    Yes ; No ; PNR (Don't know, don't say)

Other questions The survey is completed by other attitudinal questions, treated in our companion paper, Douenne & Fabre (2020a). Hereafter, we only describe questions that are used in the present paper.

50. Please select "A little" (test to check that you are attentive).
    Not at all ; A little ; A lot ; Completely ; PNR (Don't know, don't say)
51. Do you smoke regularly ? *Yes ; No*
52. How much are you interested in politics ?
    Almost not ; A little ; A lot
53. How would you define yourself ? (Several answers possible)
    Extreme left ; Left ; Center ; Right ; Extreme right ; Liberal ; Conservative ; Liberal ; Humanist ; Patriot ; Apolitical ; Ecologist
54. How do you keep yourself informed of current events ? Mainly through...
    Television ; Press (written or online) ; Social networks ; Radio ; Other
55. What do you think of the Yellow Vests ? (Several answers possible)
    I am part of them ; I support them ; I understand them ; I oppose them ; PNR (Don't know, don't say)
56. The survey is nearing completion. You can now enter any comments, comments or suggestions in the field below.

H Support rates for Tax & Dividend policies

TABLE H.1 – Support for Tax & Dividend policies at different stages of the survey.

	"Would you approve of this reform ?"		
	"Yes"	"No"	"PNR"
Initial stage (A^0)	10.4%	70.3%	19.3%
After feedback (A^F)	16.8%	63.0%	20.2%
Targeted dividend (A^T)			
bottom 20% (A^T)	19.1%	63.2%	17.7%
bottom 30%	15.0%	66.0%	19.0%
bottom 40%	17.3%	67.6%	15.1%
bottom 50%	12.8%	73.3%	13.9%
all	16.1%	67.6%	16.2%

I Relation between support and belief in progressivity

Specifications used As noticed in Section 5.3, the ambiguous responses to our priming on progressivity do not allow us to perform an IV estimation to identify the causal effect of this motive. To explore how respondents' beliefs about progressivity relate to their support for the policy, we therefore estimate simple OLS and logit regressions. Even though we control for many variables, including beliefs over other motives of support, we may suspect that the coefficients obtained remain biased by omitted variables or reverse causality. They should therefore be taken as partial correlations and not causal estimates.

We focus on the acceptance question *after information*, i.e. after asking whether the reform is progressive or not. Table I.1 presents the results of different regressions, depending on the set of controls and on the choice of variables. Columns (1)-(4) report regressions of acceptance on the broad definition of motives of acceptance : answers *not "No"* to progressivity, effectiveness and *not "lose"* to win/lose category. On the contrary, columns (5)-(6) use strict definitions for both approval and the covariates, where only *"Yes"* (or *"win"*) answers activate the dummy variables.

Results On average, believing that the reform is *not regressive* is associated with a higher *acceptance* rate by 56 p.p. (column 3), while believing it is *progressive* is associated with a higher *approval* rate by 48 p.p. (6). However, when one introduces other motives of acceptance and their interactions as covariates, with households characteristics as controls, one observes that the effect of progressivity *ceteris paribus* is lower. The marginal effect of progressivity at the sample mean — i.e. accounting for the average marginal effect of interaction terms — is 27 p.p.[32] The effect obtained for the latter motive is lower than the OLS estimate found in section 5.2, because here acceptance is taken at a later step in the survey and not right after asking about environmental effectiveness, making it less salient. Besides, one might worry that perceived progressivity would

32. Although these results are not causal, they show that 90% of those who believe in the three motives approve of the policy, along with 65-75% of those who believe in two of them.

TABLE I.1 – Effect of beliefs over progressivity on acceptance. Covariates refer either to broad (1-4) or strict (5-6) definitions of the beliefs, where strict dummies do not cover "PNR" or "Unaffected" answers.

	Acceptance (A^K) on *not "No"*				Approval ($\dot{A}^K$) on *"Yes"*	
	OLS			*logit*	*OLS*	
	(1)	(2)	(3)	(4)	(5)	(6)
Progressivity (P)	0.223***	0.214***	0.560***	0.544***	0.228***	0.482***
	(0.038)	(0.039)	(0.023)	(0.019)	(0.041)	(0.023)
Income (I, in k€/month)	0.017	0.025			0.037**	
	(0.022)	(0.019)			(0.018)	
Winner (G^P)	0.332***	0.264***			0.303***	
	(0.020)	(0.018)			(0.019)	
Effective (E)	0.258***	0.112***			0.244***	
	(0.023)	(0.021)			(0.020)	
($G^P \times E$)	0.127***	0.054*			0.126***	
	(0.034)	(0.030)			(0.037)	
Interaction : winner ($P \times G^P$)	0.183***	0.144***			0.098**	
	(0.050)	(0.044)			(0.048)	
Interaction : effective ($P \times E$)	0.172***	0.090*			0.281***	
	(0.057)	(0.050)			(0.059)	
Interaction : income ($P \times I$)		-0.009			-0.019	
		(0.012)			(0.014)	
$P \times G^P \times E$	−0.400***	−0.320***			−0.314***	
	(0.072)	(0.063)			(0.083)	
Initial tax Acceptance (A^I)		0.467***				
		(0.016)				
Controls : Socio-demo, incomes, estimated gains	✓	✓			✓	
Observations	3,002	3,002	3,002	3,002	3,002	3,002
R^2	0.460	0.586	0.162		0.391	0.130

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. For logit, average marginal effects are reported and not coefficients. The list of controls can be found in Appendix F.

be hard to disentangle from beliefs over net gains, as the latter is influenced by the former for a given income. To address this dependency, we include the interaction between progressivity and income as a covariate (2, 5). Although the coefficient is negative, in accordance with intuition, the effect is small and not significant. Adding the powerful control of initial tax acceptance in column (2) has negligible influence on the effect of progressivity, at 24 p.p. (instead of 27 p.p.), which validates our choice of preferred specification (1). Despite the powerful control, column (2) is not our preferred specification because the causal effect of environmental effectiveness is mostly captured by the covariate "initial tax acceptance", as the priming on climate change predated the initial question on acceptance. Finally, using the strict definitions of beliefs and approval yields a smaller correlation (6) but similar results when accounting for relevant controls (5), showing that the effects are not driven by a correlation between "PNR" answers.

J Willingness to pay

For respondents who believe in effectiveness of our Tax & Dividend, we are able to infer their willingness to pay (WTP) for climate mitigation by studying the acceptance rate in function of subjective gain. We adopt a common practice in the literature and define the WTP as the monetary loss that the *median* agent is willing to incur (Hanemann, 1984). Figure J.1 indicates that this WTP is about 60€/year per c.u., as this corresponds to the subjective loss below which a majority accepts the policy. This WTP is computed only among people who believe that the tax is not ineffective, as it would make little sense to assume that some people are willing to pay for an instrument that does not achieve its expected goal. Indeed, Figure J.1 shows that the "WTP" of the whole sample is zero, meaning that the median person accepts the policy only when they personally gain from it. Our method has several advantages. First, it can be interpreted as a willingness to accept as much as a willingness to pay, because our instrument is neither framed as a good to buy nor as damage to be compensated for, and net gains do not distinguish cost increases from payments received. Second, our method is more akin to revealed preferences — and hence probably less biased (Murphy et al., 2005) — than previous ones, because most studies directly ask respondents to select their preferred option for climate mitigation, be it in a contingent valuation method (Berrens et al., 2004; Cameron, 2005; Kotchen et al., 2013) or in a discrete choice experiment (Longo et al., 2008; Alberini et al., 2018). Still, our estimation has two notable limitations relative to the literature : it relies on a non-representative sub-sample, and subjective gains are endogenous with acceptance.

To compare our estimation with those of the literature, expressed per household, we have to multiply our WTP by the average number of consumption units by households : 1.6. The WTP per household we get, 96€, lies in the typical range of the literature (Jenkins, 2014; Streimikiene et al., 2019), suggesting that the protests against carbon taxation encountered in France do not reflect specific preferences for environmental policies. This finding conveys the external validity of the present paper : while the carbon tax aversion stems heavily from the French context of the Yellow Vests, aversion would probably emerge as well in another country if the first draft of a carbon tax does not properly address distributive effects or is not well communicated or designed.

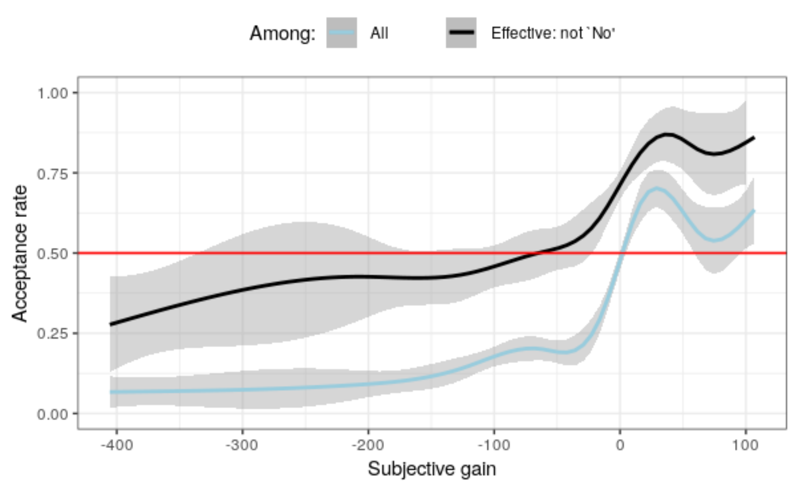


FIGURE J.1 – Acceptance by subjective gain, informing on the willingness to pay for mitigation.

K Ensuring data quality

We took several steps to ensure the best possible data quality. We excluded the 4% of respondents who spent less than 7 minutes on the full survey. We confirm that our main results are robust to choosing another cutoff than 7 minutes (see Table K.1). In order to screen out inattentive respondents, a test of quality of the responses was inserted, which asked to select "A little" on a Likert scale. The 9% of respondents who failed the test were also excluded, which yields a final sample of 3,002 respondents. Also, when the questions about a reform were spread over different pages, we recalled the details of the reform on each new page. We checked for careless or strange answers on numerical questions, such as income or the size of the household. We flagged 10 respondents with aberrant answers to the size of the household (and capped it to 12) and up to 273 respondents with inconsistent answers, such as a household income smaller than individual income, or a fuel economy higher than 90 liters per 100 km. Being flagged or response time are not significantly correlated with our variables of interest such as policy support or subjective gain (the correlation is always between −1% and 3%). An examination of flagged answers suggests that these respondents have simply mistaken the question. Among these inconsistent answers, 58 respondents have answered more than 10,000€ as their monthly income (despite the word "monthly" being in bold and underlined), with answers in the typical range of French annual incomes. We have divided these figures by 12.

TABLE K.1 – Robustness of main results to the exclusion of answers of poor quality.

	Acceptance (A^T)			Correct updating (U)		
	all	> 11 min	not flagged	all	> 11 min	not flagged
Believes does not lose (.53)	0.526***	0.547***	0.558***			
	(0.134)	(0.137)	(0.153)			
Winner, before feedback (.55)				0.542***	0.532***	0.553***
				(0.083)	(0.085)	(0.091)
Initial tax : Approves (.18)				0.180***	0.213***	0.197***
				(0.046)	(0.049)	(0.049)
Original regression : Table (column)	5.2 (1)	5.2 (1)	5.2 (1)	4.2 (2)	4.2 (2)	4.2 (2)
Effective F-statistic	15.2	14.5	11.8			
Whole sample size	2777	3165	2729	2777	3165	2729
Observations	1,978	1,825	1,826	1,370	1,261	1,242
R^2	0.320	0.318	0.326	0.142	0.150	0.155

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Two of our main results are checked on three alternative sampling restrictions : (1) inclusion of answers < 7 min, (2) exclusion of the 10% of answers < 11 min, (3) exclusion of flagged (inconsistent) respondents. Weights have been recalculated for each sample. Estimates on the original sample are reported next to variable name. See the original Tables for more details. Correlation between our main variables of interest and response time or being flagged is always below 3%. Standard errors are reported in parentheses.

Chapter IV

French attitudes on climate change, carbon taxation and other climate policies [1]

Abstract This paper aims to assess the prospects for French climate policies after the Yellow Vests crisis halted the planned increase in the carbon tax. From a large representative survey, we elicit knowledge, perceptions and values over climate change, we examine opinions relative to carbon taxation, and we assess support for other climate policies. Specific attention is given to the link between perceptions of climate change and attitudes towards policies. The paper also studies in detail the determinants of attitudes in terms of political and socio-demographic variables. Among many results, we find limited knowledge but high concern for climate change. We also document a large rejection of the carbon tax but majority support for stricter norms and green investments, and reveal the rationales behind these preferences. Our study entails policy recommendations, such as an information campaign on climate change. Indeed, we find that climate awareness increases support for climate policies but no evidence for the formation of opinions through partisan cues as in the US, suggesting that better access to science could foster support for climate policies.

Contributions Both authors contributed equally in all aspects of the work.

1. Joint with Thomas Douenne, *Ecological Economics*, 2020a.

1 Introduction

The French government is currently facing a two-sided challenge on climate policies. On the one hand, the protest of the Yellow Vests that originated in November 2018 against the planned doubling in the carbon tax — from 44.6 to 86.2€/tCO_2 in 2022 — led the government to halt the increasing trajectory that started at 7€/tCO_2 in 2014. On the other hand, a large campaign called "Affaire du siècle"started in December 2018 against its inaction for the environment, gathering over two millions signatories in a month. It is so far unclear how the tension between these two *a priori* antagonistic objectives will be resolved. In particular, one may wonder whether the two movements involve distinct groups with opposite interests, or rather reflect a commonly perceived inadequacy of the solution proposed by the government to address the climate threat.

This paper aims to understand French perceptions over the carbon tax and other climate policies. It builds on a new survey conducted on a sample of 3,002 respondents representative of the French population. Our survey contains questions to assess respondents' knowledge about climate change (CC) and their perceptions over its causes and consequences. As the paper was primarily motivated by the failed attempt to increase the French carbon tax, we examine in detail attitudes towards this instrument. We propose to respondents a Tax & Dividend policy, i.e. a carbon tax whose revenue would be returned lump-sum uniformly to all adults. This policy differs from the one proposed by the government, since the revenue would have been used to fund the general budget instead. We identify respondents' expected winners and losers, and the perceived problems and benefits of this instrument. We devote particular attention to the issue of mobility that appears critical in the current debate. We then turn to the support for a carbon tax with alternative uses of the revenue, such as more targeted transfers, earmarking, and double-dividend strategies. We also study the support for other climate policies, including norms and other Pigouvian taxes, and local policies for urban transport. Finally, we identify the determinants of attitudes over both climate change and climate policies, as well as the link between the two.

For a general presentation of attitudes over climate change, we suggest Whitmarsh & Capstick (2018), while for a more specific review on their trends and determinants, we redirect to Brechin (2010) and Ziegler (2017). Our paper contributes mainly to a growing literature on the political economy of climate policies. As an entry point to previous related studies, refer to Maestre-Andrés et al. (2019) who review the perceptions of climate policies, Drews & van den Bergh (2016) who review the determinants of their support, and to Carattini et al. (2018) for a comprehensive overview on attitudes over the carbon tax.

A large extent of the literature has focused on the carbon tax. Using a post-electoral survey in Switzerland, Thalmann (2004) finds that political leaning, education and self-interest are correlated with acceptance. Subsequent literature has confirmed the importance of self-interest (e.g. Fischer et al., 2011; Baranzini & Carattini, 2017) although Kallbekken & Sælen (2011) find that perception of the tax' effectiveness and its distributive properties play a larger role in Norway. The critical role of the tax' effectiveness has been confirmed by numerous contributions that pointed out the higher acceptance of taxes whose revenue was earmarked towards green investments (e.g. Sælen & Kallbekken, 2011; Baranzini & Carattini, 2017). Similarly, studies have confirmed that people tend to prefer more progressive schemes (Brannlund & Persson, 2012; Gevrek & Uyduranoglu, 2015) and more targeted revenue recycling (Kallbekken et al., 2011). In a companion paper (Douenne & Fabre, 2020b) based on the same survey, we show that French people reject the carbon tax because of biased beliefs over its properties, but if convinced about their own gain, the environmental effectiveness and the progressivity of the mechanism, they would largely approve it. Among the potential barriers to the implementation of carbon taxation, Kallbekken & Aasen (2010) emphasize the importance of the availability of alternatives to fossil fuels. When these alternatives are lacking or not easily affordable, carbon taxation is perceived as just a pretext to increase taxes (Dresner et al., 2006a; Klok et al., 2006). Finally, as shown by Harring & Jagers (2013), trust in politicians is also a key factor for carbon tax acceptance, which relates to the recent findings of Rafaty (2018) who shows that higher political distrust is associated with weaker climate policies.

While a lot of attention has recently been put on carbon taxation, fewer studies have investigated attitudes towards other climate policies. Yet, as highlighted by Stern & Stiglitz (2017) and Stiglitz (2019) a single price instrument may not be the best response to climate change in a second-best world. The main factors driving people's preferences between various policies appear to be their degree of coercion, the behavior targeted by the policy (de Groot & Schuitema, 2012), and the perceived cost. It follows that subsidies are in general preferred over taxes (e.g. Tobler et al., 2012; Cherry et al., 2017), and more voluntary measures over hard regulations (Attari et al., 2009). The present paper contributes to the literature by providing a comprehensive analysis of perceptions and attitudes towards CC, carbon taxation and other climate policies in a country that has recently experienced a carbon tax increase and a large debate ensuing. As it is based on an unusually large sample representative of the French population, the paper also goes further than previous studies in identifying the heterogeneity in people's attitudes over climate policies.

Section 2 presents the survey. Section 3 describes attitudes towards climate change. Section 4 focuses on tax & dividend policies, its perceptions, and the reasons explaining the low support for this policy. Section 5 studies the support for alternative revenue recycling mechanisms as well as for other climate policies. Section 6 examines the heterogeneity in attitudes expressed in the previous sections and characterize their determinants. Section 7 concludes. Finally, further material can be found in Appendix.

2 The survey

2.1 Presentation of the survey

We collected 3002 responses in February and March 2019 through the survey company Bilendi. This company maintains a panel of French respondents to whom they can email survey links. Respondents are paid 3€ if they fully complete the survey. The respondents who choose to respond are first filtered through some screening questions which ensure that the final sample is representative along six socio-demographic characteristics : gender, age (5 brackets), education (4), socio-professional category (8), size of town (5), and region (9).

The full survey in French can be seen online, [2] the questions analyzed are translated in Appendix C, and the code is available on github. Most figures can be found in French on github or in Douenne & Fabre (2019). Figure 2.1 presents in a diagram the sequence of questions.

The survey starts by asking for households' socio-demographics and energy usage. Then, we describe Tax & Dividend reforms where the revenues of an increase in the French carbon tax by 50€/tCO_2 are redistributed uniformly to all adults. We first allocate respondents randomly to a sectoral Tax & Dividend reform, which concerns either gas and heating oil (i.e. housing energy), or gasoline and diesel (i.e. transportation energy). Respondents are asked to estimate their reaction

2. preferences-pol.fr/doc_q.php#_e

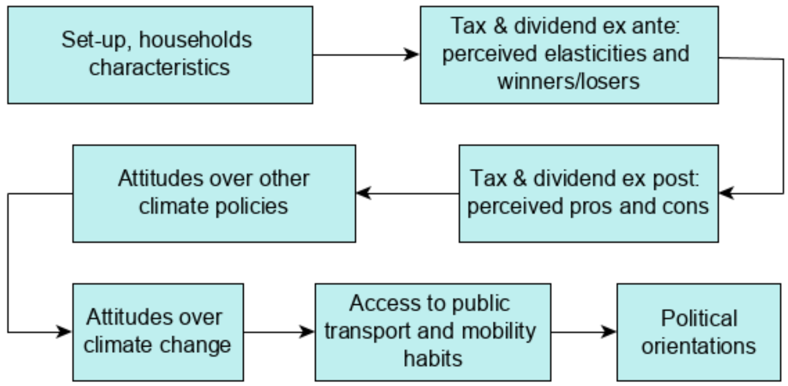


Figure 2.1 – Diagram of the sequence of questions.

to price changes, the reaction of French people, and how much purchasing power they would gain or lose from the policy. To this end, exact price variations and the amount transferred are provided, and respondents can choose among answers given in different brackets. Then, we study perceptions and support for a Tax & Dividend on both sectors combined, before and after providing new information to the respondents. This new information is either that the policy is progressive, or whether their household would win or lose some purchasing power through the reform. Before providing information, we let respondents pick the categories of losers and winners from the reform ; and after the information, they choose the benefits and the problems associated with this reform. We study these perceptions of the policy in the present paper, but please refer to our companion paper (Douenne & Fabre, 2020b) for details and analyses on the other questions about Tax & Dividend reforms.

2.2 Eliciting attitudes

After inquiring about the support for Tax & Dividend, we ask respondents to assess on a Likert scale different ways to recycle the revenues of a carbon tax. On another Likert scale, we examine opinions on other climate policies, notably new norms or Pigouvian taxes. We then measure respondents' knowledge about climate change by asking for its origin (anthropogenic or natural), its causes (in terms of gases and activities), which region it will most affect (between India and the European Union), and what reduction of emissions is needed by 2050 to respect the +2°C target. At the same time, we assess attitudes over climate change by asking respondents about the frequency with which they talk about it, the gravity of its consequences, the generations it will severely affect, and the entities responsible for its occurrence. We continue by surveying if and how climate change influences one's decision to have a child, under which conditions one would be ready to change their lifestyle to fight climate change, and whether one would be ready to adopt a sustainable lifestyle if policies were aligned to this goal. We also ask questions about diesel taxation. Then, we evaluate the respondents access to public transport, their mobility habits, and if there is room for changing these habits. Finally, we ask for their political preferences, including their positioning in relation to the Yellow Vests. The survey ends with a text box where the respondents can leave a comment.

3 Perceptions and Attitudes over Climate Change

To fully understand the root motivations to the support or rejection of climate policies, we first analyze the knowledge and perceptions over CC, as well as the reaction that people expect to address this phenomenon. As the paper focuses on explaining attitudes over policies, we relegate to Appendix D.1 some figures and some results from other surveys.

3.1 Knowledge

As shown in Figure 3.1, knowledge that CC is anthropogenic is widespread (72%) and the share who do not believe in climate change (CC) is marginal (4%). The level of knowledge on the anthropogenic origin of CC is similar to that of other Western countries (Leiserowitz, 2007; Lee et al., 2015; Stokes et al., 2015a) : it is 66% in the U.S. (Gallup, 2019)for example. At the same time, knowledge about climate science appears limited. Although 77% of people correctly tick "CO_2" as a greenhouse gas (GHG), Figure 3.2 shows that almost as many people tick particulate matter (39%) as methane (48%). Admittedly, understanding the impacts of activities is more useful than erudition about chemical factors, but here again, knowledge is quite low. We assess such awareness using pairs of comparable activities whose GHG footprint differ by a factor 20 (beef steak vs. pasta, plane vs. train) or whose footprint are similar (nuclear vs. wind power). [3] We ask whether it is true that one activity emits 20 times more GHG than the other, as a way to express precisely that one is "much more" polluting than the other. For each pair, around half of the sample is correct. The bulk of respondents pick two correct answers out of three (44%), but more get them all wrong (19%) than all right (15%).

Not only do most people fail to fully understand the factors and consequences of CC, but they also fail to grasp the degree of reaction needed to tackle it. When informed that "each French person emits on average the equivalent of 10 tons of CO_2 per year" and asked what the figure should be in 2050 to "hope to contain global warming to +2°C in 2100 (if all countries did the same)", 59% answer 5 or more (see Figure 3.3). Only 17% select a correct answer : 0, 1 or 2 (see Appendix A for why these are correct).

Millner & Ollivier (2016) propose several mechanisms to explain people's lack of understanding about climate change : in addition to the difficulty of grasping gradual changes, they emphasize the complexity of drawing a causal link between diffuse causes and distant consequences. [4] Failing to assimilate the underlying channels may blur the link between people's own behavior and consequences for the climate. Thus, we can wonder if people understand who would have to make the mitigation effort in a sustainable scenario, i.e. who is responsible for CC.

3. Appendix A.1 details how the figures were obtained.
4. Actually, even MIT students struggle with this (Sterman, 2008).

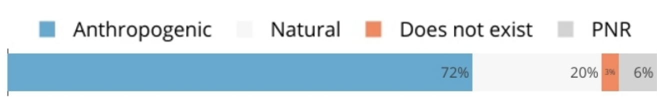
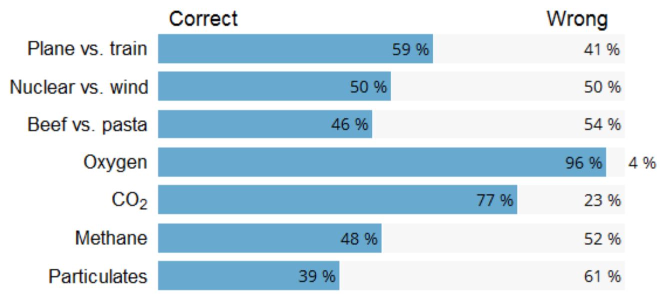


FIGURE 3.1 – Perceived cause of climate change.

FIGURE 3.2 – Perceived factors of climate change.



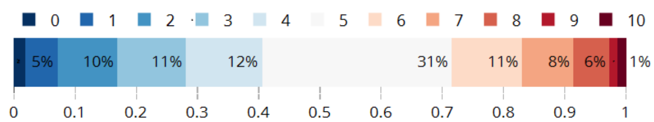


FIGURE 3.3 – Perceived GHG emission p.c. required in 2050 to limit global warming to +2°C (in tCO_2eq/yr), given that it is now 10.

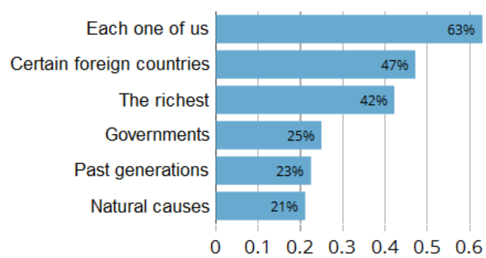


FIGURE 3.4 – Entities perceived responsible for climate change.

3.2 Positions

As shown in Figure 3.4, 63% acknowledge that "each one of us" is responsible for CC, and less people ascribe the responsibility to "certain foreign countries" (47%), "the richest" (42%), or any other agent. Not only do people seem lucid concerning the agents causing CC, but a vast majority also foresees worrying consequences if humanity does nothing to limit it. Figure 3.5 shows that 18% see the impacts as "cataclysmic, humankind would disappear", 28% as "disastrous, lifestyles would be largely altered", 34% as "grave, because there would be more natural disasters", while only 11% think damages would be "small, because humans would be able to live with it" or "insignificant, or even beneficial".

Overall, these results indicate that most people understand the fundamentals of climate issues, including the root causes and the scale of the problem, but that only a minority has thought of CC deeply enough to comprehend its factors and the pathways to tackle it.

3.3 The Reaction Needed

Given that many people may not realize the extent of the transition needed to reach sustainability, and that others may be discouraged precisely by the sheer magnitude of such a transition, we can wonder how willing people are to contribute to its success. An encouraging finding for the

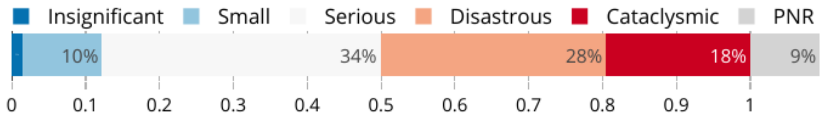


FIGURE 3.5 – Perceived gravity of climate change.

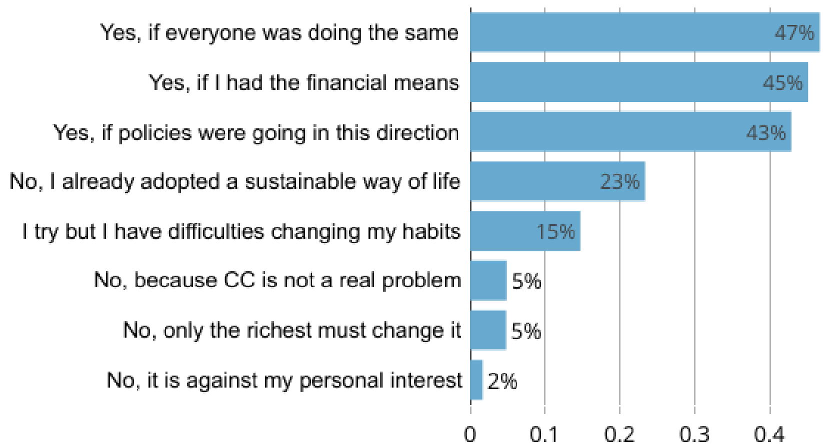


FIGURE 3.6 – Respondent could change their lifestyle under a condition.

transition is that 65% are "willing to adopt an ecological lifestyle (i.e. eat little red meat and make sure to use almost no gasoline, diesel nor kerosene)", assuming that "all states in the world agree to firmly fight climate change, notably through a transition to renewable energy, by making the richest contribute, and imagining that France would expand the supply of non-polluting transport very widely", while only 17% answer "No" (the others do not take a side). While the phrasing removes most grounds against a change in lifestyle, we inquire under which conditions people would be willing to adopt such a change (see Figure 3.6). 82% of respondents would be willing to change their lifestyle under at least one of the three conditions proposed : sufficient financial resources, an alignment of policies to this goal, or an adjustment of others' behavior (about 45% each).

Finally, a substantial fraction of people incorporates ecological constraints in their life choices. Indeed, 15% call themselves ecologist (the most picked political identity outside of the left-right spectrum, see Appendix F), 23% claim they already adopted a sustainable way of life, and 20% say the CC "has had or will have an influence in their decision to have a child".

4 Attitudes over Carbon Tax and Dividend

Most French people are aware and concerned about climate change and claim to be willing to exert efforts to fight it. Yet, the government's attempt to introduce a carbon tax to deal with French emissions resulted in a widespread popular protest. To understand this paradox, we investigate the preferences over a Tax & Dividend policy : an increase of 50€/tCO_2 in the current French carbon tax, with a uniform lump-sum redistribution of the additional revenue to all adults. This policy differs from the official one whose revenue was mostly used to fund the general budget. Respondents are given the associated increase in energy prices so that the direct costs are salient : +13% (resp. +15%) for gas (resp. heating oil), and +0.11€ (resp. +0.13€) for a liter of gasoline (resp. diesel).

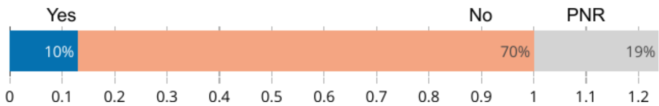


FIGURE 4.1 – Approval of Tax & Dividend.

They are also told that the transfer would amount to 110€ per adult annually.

4.1 Widespread rejection

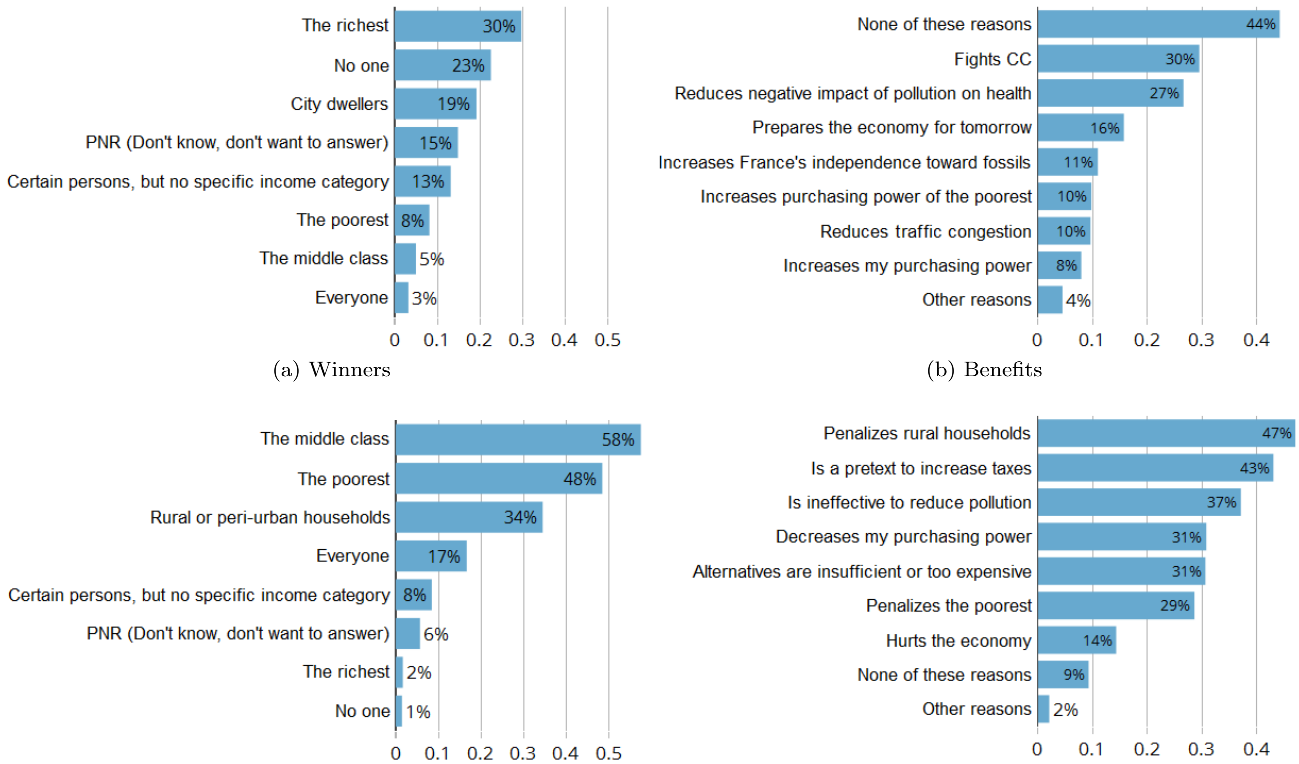
French people would largely reject the proposed policy. Only 10% of our respondents declare they would approve it, while 70% say they would not (see Figure 4.1). As shown in our companion paper (Douenne & Fabre, 2020b), this rejection can be explained by erroneous perceptions about the policy's outcome, such as an overestimation of its impact on one's purchasing power. For instance, 30% of people who use neither gas nor heating oil believe their household would lose from an equally redistributed increase in taxes on these goods. Interestingly, the salience of costs appears critical in people's answer. At a later stage of the survey, we ask respondents whether they would agree to increase the carbon tax if the revenue was returned to all households, without mentioning the impact on prices. The question is asked along with a package of other environmental policies (see section 5). In this case — where the benefits are more salient than the costs — we find a much higher approval rate of 37%. Another survey conducted in March 2019 (OpinionWay, 2019) assesses acceptance for a *reintroduction* of the carbon tax increase in 2021. They find intermediary results with an approval rate of 21%.

The low level of acceptance observed partly results from recent events. In July 2018, ADEME (2018) found that 48% of French people thought it was desirable to increase the carbon tax, a figure similar to those of other countries (Brechin, 2010). The discrepancy between 2018 and 2019 can be explained by the "campaign effect" highlighted by Anderson et al. (2019) : support for a carbon tax decreases substantially after it enters the public debate. Indeed, the French carbon tax was brought under the spotlight in the end of 2018, after high oil prices triggered the Yellow Vests movement.

4.2 Perceived winners and losers

Figure 4.2 represents the share of respondents who expect different household categories to win or lose from the policy. Income appears to be the most critical divide, with a non-monotonic relationship. 30% of respondents expect the richest to win while only 2% think they would lose. On the contrary, 40% more people think that the poorest would lose rather than win, a difference even higher for the middle class — the category most expected to lose — at 53%. To half of respondents, we framed the question about winners and losers specifically in terms of "purchasing power". The objective was to see if some categories were commonly seen as losing in welfare although they could gain in monetary terms, or conversely. The results look very much alike for both formulations, except that the shares of people expecting poorer households to gain (5.8%) and richer households to lose (0.9%) are significantly larger when asked in terms of purchasing power : 10.2% and 2.1%, respectively (see Appendix E). Overall, respondents perceive the Tax & Dividend as regressive. As shown by a large body of literature (e.g. West & Williams, 2004; Bento et al., 2009; Williams et al., 2015), and more specifically in our companion paper (Douenne & Fabre, 2020b), these beliefs are at odds with the true distributive effects of this proposed policy.

FIGURE 4.2 – Perceived winners & losers and pros & cons from Tax & Dividend



(a) Winners (b) Benefits (c) Losers (d) Problems

Beyond the income dimension, people tend to identify city dwellers as potential winners from the Tax & Dividend (third position at 19%), while rural and peri-urban households are rather expected to lose (third position at 34%). We also see that people report on average more categories for expected losers than winners : 1.74 vs. 1.16. The high ranks of "no one" for winners (second) and of "everyone" for losers (fourth) further suggest that respondents do not see our policy as a zero-sum game.

4.3 Perceived pros and cons

Previous studies have highlighted that distributive effects are a critical determinant of carbon tax acceptance (e.g. Kallbekken & Sælen, 2011; Brannlund & Persson, 2012; Gevrek & Uyduranoglu, 2015). When asked about the problems associated with the Tax & Dividend, the main response is that the tax would penalize rural households (47%). Interestingly, this concern comes before the threat that the tax could penalize the poorest (sixth position with 29%), although more people report the poorest as a category of people expected to lose. The second and third concerns are that the policy is simply a pretext to increase taxes (43%) — a worry documented by Dresner et al. (2006a) and Klok et al. (2006) — and that it would be ineffective to reduce pollution (37%). Related to this last point is the perceived lack of alternatives, seen as insufficient or too expensive (31%). This problem has been previously stressed by Kallbekken & Aasen (2010) in a focus group study :

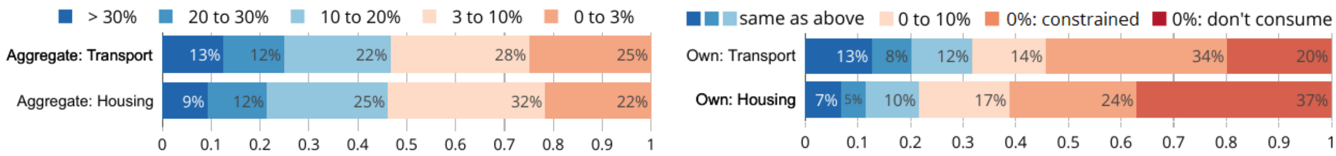


Figure 4.3 – Perceived aggregate and own elasticities.

people do not see the point of taxing fossil fuels if they cannot substitute for other technologies. This last reason is stated as frequently as concerns over the impact on one's own purchasing power (fourth with 31%). As shown in Douenne & Fabre (2020b), self-interest largely affects acceptance of the Tax & Dividend, but this concern could sound too egoistic when stated in a direct way. While previous studies have pointed out concerns over the negative impact of carbon taxation on the economy (e.g. Thalmann, 2004; Carattini et al., 2017), this problem comes last (14%) and does not seem to represent an important obstacle for public support in the current context.

Respondents are suggested to pick at most three answers among both problems and benefits. On average, respondents pick 2.36 problems — and 53% pick at least 3 — against 1.14 benefits, excluding the most popular : "None of these reasons" (44%). This option comes far ahead of the second and third, "fight climate change" (30%) and "reduces negative impact of pollution on health" (27%). Still, environmental benefits are much more cited than economic ones. This result is likely due to people's pessimism about the outcome of the policy, but it might also reflect the limited importance given to economic consequences of the carbon tax, as already suggested by problems commonly cited.

4.4 Consumption and mobility constraints

The perceived problems identified above suggest a rationale for people's opposition towards carbon taxation : if people think the tax is ineffective, because their consumption is constrained and affordable alternatives are lacking, then taxing carbon can be perceived as a pretext to increase taxes.

4.4.1 Perceived elasticities

In order to understand to what extent people feel constrained with respect to their energy consumption, we elicit their subjective price elasticity for transport and domestic energies. We adopt the phrasing of Baranzini & Carattini (2017) and ask the expected decrease in energy consumption that would follow an increase in prices. To avoid dealing with small percentages, which people usually find more difficult to compare, we ask for the reaction to a 30% increase in the price of heating (or equivalently, an increase of 0.50€ per liter in fuel prices). Although sufficiently high to foster a significant response on demand, these changes are realistic in the medium run, and should not lead people to report long-term elasticities. Respondents may select their answer among 5 brackets. They are asked to estimate their own reaction as well as that of French people. Figure 4.3 presents the results.

54% (resp. 61%) of respondents consider that such an increase in prices would not lead them to reduce their transport (resp. domestic) energy consumption. This expected inelastic behavior is mainly due to mobility constraints for transport (64% of cases) while it mostly reflects a non-fossil heating type for housing (61%). Excluding people reporting inelastic behavior because of insignificant initial consumption, about 40% of people feel constrained and expect to not lower their consumption following price increases. Still, respondents perceive transport fuel price elasticity of French people at −0.45 on average, and their own elasticity at a consistent −0.36 (after re-weighting by fuel expenditures). Concerning housing energy, aggregate and personal subjective elasticities are respectively −0.43 and −0.33. Overall, these subjective elasticities compare well to the ones found in the literature for French households, although they are slightly over-estimated (in absolute value) for housing. [5]

4.4.2 Mobility and public transport

To assess the level of dependence on automobiles, which we include as a determinant for preferences in Section 6, we study mobility habits and access to public transport. Figure 4.4 indicates that 65% of employed people drive to work, and that car usage is even more common for grocery shopping or leisure activities. This figure is confirmed by the national transport survey ENTD (2008) conducted by Insee and analyzed in Pappalardo et al. (2010), which reveals that a majority still uses a car for trips of 1 to 2 km. Even though 73% live within a 10 minute walk to a public transit stop (Figure 4.5), coverage and frequency of public transport is often too low (Figure 4.6) to compete with the speed, comfort, and flexibility of automobiles. Indeed, 58% of those who commute by car declare that they could neither substitute it with public transport nor walking or cycling, and only 15% could use one of these alternative without major difficulties (Figure 4.7). Further evidence indicates that the lack of alternatives is a main factor for car usage, besides apparent taste for a vehicle that remains a symbol of freedom. Figure 4.8 shows that 52% of respondents state that supply of public transport where they live is "insufficient" or "decent, but should be increased", while 40% find it "satisfactory" or "limited, but sufficient". From this perspective, "green public investments and carbon taxes appear to be complementary, and in the timing of climate policy it would be justified to carry out the former before implementing the latter", as Bureau et al. (2019) suggest. Alongside an increase in the supply of alternatives, climate policies could also address the demand for mobility, e.g. by revitalizing town centers and limiting urban sprawl.

5 Attitudes over Other Policies

The previous section has shown that our Tax & Dividend was largely rejected by French people. As climate policies are urgently needed, it appears necessary to assess whether other designs and instruments would be met with a higher support. This section first examines public opinion about

5. For transports, estimates from the literature lie around −0.4 (Clerc & Marcus, 2009; Bureau, 2011; Douenne, 2020). For housing, the values are lower, typically around −0.2 (Clerc & Marcus, 2009; Douenne, 2020).

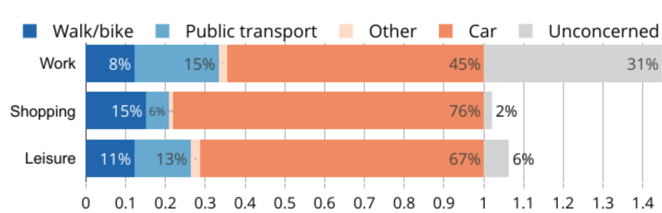


FIGURE 4.4 – Mode of transportation by activity.

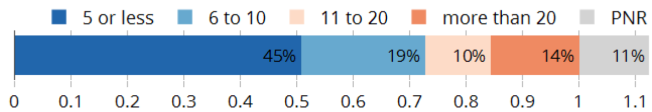


FIGURE 4.5 – Walking distance to the nearest stop, in minutes.

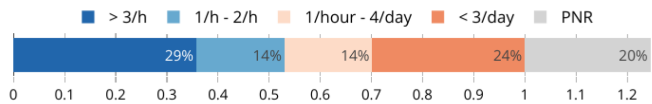


FIGURE 4.6 – Frequency of public transport at the nearest stop.

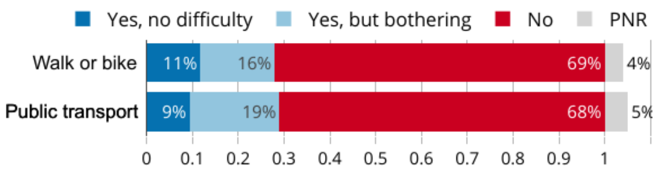


FIGURE 4.7 – Among those who commute to work by car, possibility to change the transportation mode, depending on the alternative.

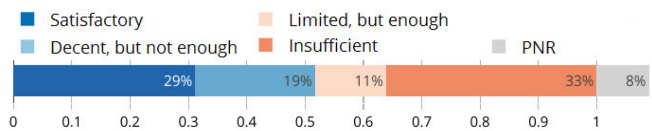


FIGURE 4.8 – Supply of public transport where the respondent lives.

several alternative uses for the carbon tax revenue and then turns to other environmental and climate policies.

5.1 Preferred Revenue Recycling

We asked respondents to what extent they would accept an increase in the carbon tax for different uses of the revenue. As the exact cost of the tax was not specified, the benefits of the revenue recycling were made relatively more salient, which explains higher acceptance rates compared to our Tax & Dividend. Still, this question enables to compare answers relative to one another.

5.1.1 Investments in energy transition

Figure 5.1 reports people's responses to each proposed scenario. Overall, the preferred revenue recyclings are investments in the energy transition. This result is consistent with various papers showing that earmarking the revenue of the tax for environmental purposes largely increases public support (for a review of the literature, see for instance Kallbekken & Aasen, 2010; Carattini et al., 2018). As people tend to see carbon taxation as effective only if it finances green investments (Sælen & Kallbekken, 2011), these policies legitimize the implementation of a tax and increase its acceptance. In addition, the large approval for a policy investing in non-polluting transport can be explained by people's desire for mobility alternatives, the lack of which was identified as an important problem with our Tax & Dividend (see section 4).

5.1.2 Transfers to households

While previous literature has shown that distributive concerns matter for carbon tax approval, the common tool proposed by economists to address this issue — lump-sum transfers — is not met with resounding support. Out of the nine proposed mechanisms, the standard flat recycling comes last (with 37% approval), and a transfer targeted to the bottom 50% comes seventh (46%). Consistent with our previous finding that people are concerned that the carbon tax may penalize rural and peri-urban households, the preferred "lump-sum" transfer is the one targeted to people constrained with respect to their consumption of petroleum products (fifth with 55% approval).

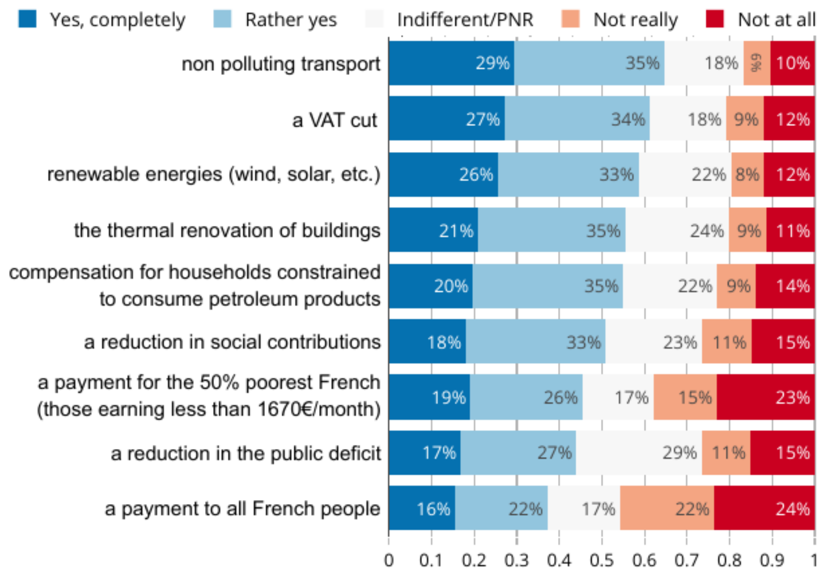


FIGURE 5.1 – Approval of a carbon tax if its revenue finances...

These results echo the findings of Kallbekken et al. (2011) who showed that people tend to prefer more narrowly targeted revenue recycling, possibly because of distributional concerns. The lower support for transfers is the only result that departs from the preferred revenue recycling in Germany and in the U.S., documented by Beiser-McGrath & Bernauer (2019).

The relatively low support for compensation mechanisms should however not be understood as a lack of concern about purchasing power or distributive effects. As shown in section 4, the distributive properties of lump-sum transfers are not well understood. Perhaps surprisingly, the second preferred mechanism for revenue recycling is a reduction in the VAT rate (61% approval). The main rationales for this support are the benefits to one's purchasing power and the perceived distributive effects. As the VAT is known to be a regressive tax, people may perceive it fair to compensate an increase in the regressive carbon tax with a decrease in the VAT. Although such a mechanism would be less favorable to poorer households — who spend less in VAT in absolute value, and would therefore receive less than from a uniform transfer — it may not be perceived as such.

5.1.3 Double dividend and public deficit

The last two options propose to use the carbon tax revenue to reduce social contributions, or the public deficit. These mechanisms come respectively in sixth and eighth position with 51% and 44% of approval. These results can be linked to the low level of concern regarding the impact of a carbon tax on the economy documented in section 4. They are also consistent with previous focus group studies (e.g. Kallbekken & Aasen, 2010), including in France where Deroubaix & Lévèque (2006) found that people did not understand why the revenue of an environmental tax reform should be used to tackle unemployment.

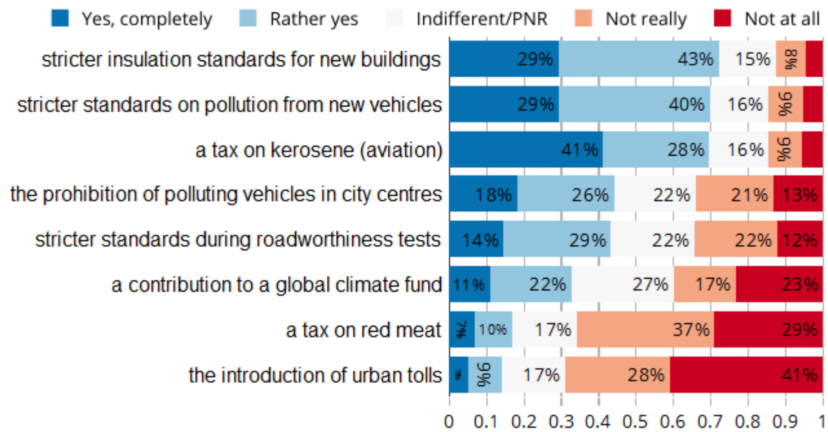


Figure 5.2 – Approval of different climate policies.

5.2 Other Instruments

Under a binding acceptability constraint, alternative instruments become relevant, even if Pigouvian taxes may be more cost-effective (e.g. Goulder & Parry, 2008). To elicit people's preferred environmental policies, we ask respondents whether they would support eight different propositions. To make these questions easier to answer, the exact mechanisms and their associated costs and benefits are unspecified. The answers reported should therefore be taken cautiously as people could change their mind once faced with clear trade-offs. Still, this exercise is informative about people's first reactions to different proposals.

5.2.1 Other Pigouvian taxes

Figure 5.2 shows that among the eight options, the most strongly supported is a tax on kerosene (70% of "Yes" including 41% of "Yes, completely"). The main rationale could be a broadly perceived effectiveness of the tax if people view aviation as an important source of emissions, and the distributive effect of such policy since richer people fly more.[6] In sharp contrast, only 17% of our survey respondents approve a tax on red meat, a policy ranked second-to-last. One could explain this lower acceptance rate by the belief that such policy would be ineffective, as we have shown in section 3 that less than half of respondents know that beef has a high carbon footprint. Additional reasons for its rejection could be the perceived negative impact on purchasing power, and the feeling that the policy is too coercive and targets a behavior difficult to change (de Groot & Schuitema, 2012). Overall, this evidence confirms that people are not opposed to Pigouvian taxes *per se*, and that acceptance varies significantly depending on the target and the perceived outcome of the instrument.

5.2.2 Norms

Among all proposed instruments, the two most approved are norms. 72% and 70% of respondents declared being in favor of stricter standards for the insulation of new buildings and for the pollution

6. In France in 2008, people in the top income decile travelled by plane about seven times more than the bottom 50% of the income distribution (Pappalardo et al., 2010). Furthermore, kerosene's emissions are taxed only through the EU-ETS, hence at a far lower rate than diesel and gasoline. This discrepancy has been highlighted in the public debate.

of new vehicles, respectively. It is unclear to what extent people are aware of the "hidden costs" of such policies. For instance, fuel economy standards in the US have been estimated to be three to six times more costly than a tax on gasoline for similar abatement levels (Jacobsen, 2013), and as possibly more regressive (Jacobsen, 2013; Davis & Knittel, 2019; Levinson, 2019). The exact properties of these instruments are of course specific to their design, but it is likely that their popularity partly reflects the underestimation of their costs.

For urban transport policies as well, standards are preferred to price instruments. While the prohibition of polluting vehicles in city centers comes fourth on the list of preferred options with 44% approval, the introduction of urban tolls comes last with only 14%. In a survey on urban road pricing, Jones (1998) identifies the main deterrent for these mechanisms. While some are specific to congestion charges, the other perceived problems are very much alike those identified for our Tax & Dividend : ineffectiveness, unfairness and the feeling that it is just another tax.

5.2.3 Diesel taxation

The strong opposition of the Yellow Vests against energy taxes did not only lead the government to reverse the planned carbon tax trajectory. The additional tax increases initially scheduled for diesel — to catch-up with the currently higher rates imposed on gasoline despite diesel's high social cost from air pollution — have also been abandoned.[7] In our survey, we ask respondents whether they would therefore accept an increase in diesel tax to catch up with that of gasoline. As illustrated by Figure 5.3, 59% of respondents answer they would not, while 29% say they would (12% "PNR"). Among the 57% of households who own a diesel vehicle, the opposition augments to 80%. The geographic difference is also striking as 73% of rural households would be opposed, vs. only 40% of those living in the Paris agglomeration. As shown in Appendix G, these two determinants appear as the most important divides with respect to diesel taxation.

6 Determinants of Attitudes

To understand what factors foster environmentally-friendly attitudes, we explore the socio-demographic determinants of attitudes over CC, the correlations between knowledge and perception of CC, and how these attitudes over CC as well as socio-demographics shape preferences for policies.

6.1 Attitudes over climate change

Table 6.1 shows the main socio-demographic determinants of different attitudes towards CC : the knowledge that CC is anthropogenic (columns 1-3), an index of knowledge about CC (4) and the perception that CC is "disastrous" or "cataclysmic" (5-6). To build the index of knowledge, we aggregate different variables corresponding to the different kinds of knowledge about CC identified by Kiel & Rost (2002) (see also Hoppe et al., 2018, for a summary).

7. Three increases of +0.026€/L were initially scheduled for January 2019, 2020 and 2021.

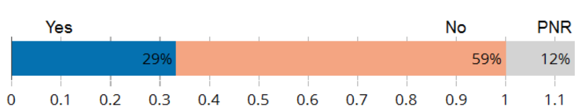


Figure 5.3 – Approval of a catching-up of the diesel tax.

We first compute a score for the question asking the emission target p.c. required to limit CC (see section 3.1). Denoting t as the respondent's answer (from 0 to 10 tCO_2/yr), we define the score as :

$$\text{score emission target} = \begin{cases} 3 & \text{if } t \leq 2 \\ 2 & \text{if } t \in [3;4] \\ 1 & \text{if } t \in [5;6] \\ 0 & \text{if } t \geq 7 \end{cases} \tag{6.1}$$

and we then aggregate this score with other answers :

$$\begin{aligned} \text{knowledge} = 3 \cdot \text{CC anthropogenic} - 2 \cdot \text{CC doesn't exist} \\ + \ \text{score factors} + \text{score emission target} \end{aligned} \tag{6.2}$$

where "score factors" is the sum of correct answers to factors of CC (see Figure 3.2), and the two first variables in the formula are dummies. The relative weights of the variables correspond to the loadings of a one-factor analysis, ensuring that our index captures the most determinant elements of knowledge. [8] The original index ranges from -2 (no respondent) to $+13$ (22 respondents), and has quartiles of 6, 8 and 9. In the regressions, we normalize this index by subtracting the mean (7.6) and dividing by the standard deviation (2.5). Finally, we run OLS regressions of the three attitudes over CC on various socio-demographics, household characteristics, and political orientation. We report only the most relevant variables, but describe the entire list of covariates in Appendix B.1. We confirm that logistic regressions yield similar results (see Appendix I).

The best predictors of attitudes over CC corresponds to political orientation, and in particular identifying as an ecologist, one's positioning towards the Yellow Vests, and left-right leaning. Political orientation shapes attitudes in a consistent manner : being ecologist, more left-wing or less supportive of the Yellow Vests is always associated with higher "concern over CC", i.e. better knowledge and higher pessimism. Interest into politics (measured on a scale "almost not"/"a little"/"a lot") also leads to higher concern, but to a lesser extent. Two observations on the left-right leaning deserve comment. First, the 40% of people indeterminate relative to this spectrum (see Appendix F for the descriptive statistics) have attitudes close to the center-right. Second, the variations predicted in the dependent variables are as high across the Yellow Vests positionings as across the traditional left-right spectrum. For instance, knowledge about CC is *ceteris paribus* lower by 0.50 standard deviation (s.d.) for people part of the movement than for those who oppose it, which is comparable to the spread of 0.41 s.d. between extreme-right and extreme-left people (4).

Two socio-demographics are also consistently related to attitudes over CC : age and level of education. On average, the younger and the more educated one is, the more one is concerned by CC. People aged 18-24 may appear to have slightly lower knowledge and lower pessimism than people of prime age *ceteris paribus*, in columns (1,4,5) ; but this is because their concern is mostly captured by the employment status modality "student", not shown in the table. Overall, the generation with the least concern is undeniably those aged over 65. For instance, without any control, they are 20 percentage points (p.p.) less likely to believe that CC is anthropogenic than young adults (2) — though most of this effect is explained by a lower level of education (1).

8. See Appendix H for more details.

TABLE 6.1 – Determinants of attitudes towards climate change (CC).

	CC is anthropogenic			Knowledge about CC	CC is disastrous	
	(1)	(2)	(3)	(4)	(5)	(6)
Interest in politics (0 to 2)	0.032**			0.137***	0.051***	
	(0.013)			(0.028)	(0.014)	
Ecologist	0.135***			0.404***	0.192***	
	(0.024)			(0.053)	(0.027)	
Yellow Vests : PNR	−0.098***			−0.142**	−0.093***	
	(0.033)			(0.071)	(0.036)	
Yellow Vests : understands	−0.038*			−0.100**	−0.051**	
	(0.022)			(0.048)	(0.024)	
Yellow Vests : supports	−0.098***			−0.223***	−0.061**	
	(0.024)			(0.051)	(0.026)	
Yellow Vests : is part	−0.207***			−0.498***	−0.105**	
	(0.043)			(0.093)	(0.047)	
Left-right : Extreme-left	0.111**		0.109	0.295**	0.075	0.005
	(0.056)		(0.077)	(0.122)	(0.062)	(0.084)
Left-right : Left	0.074***		0.070	0.137**	0.099***	−0.025
	(0.027)		(0.046)	(0.059)	(0.030)	(0.051)
Left-right : Center	0.013		0.039	0.093	0.021	−0.089*
	(0.030)		(0.044)	(0.065)	(0.033)	(0.048)
Left-right : Right	−0.029		−0.017	−0.039	−0.023	−0.143***
	(0.029)		(0.045)	(0.062)	(0.032)	(0.049)
Left-right : Extreme-right	−0.014		−0.019	−0.117	0.025	−0.086
	(0.034)		(0.055)	(0.074)	(0.037)	(0.060)
Diploma : *CAP* or *BEP*	0.040*		0.033	−0.004	−0.014	−0.010
	(0.022)		(0.023)	(0.049)	(0.025)	(0.025)
Diploma : *Baccalauréat*	0.065**		0.115***	0.145**	0.030	0.133***
	(0.027)		(0.028)	(0.058)	(0.029)	(0.031)
Diploma : Higher	0.086***		0.159***	0.266***	0.096***	0.240***
	(0.027)		(0.027)	(0.059)	(0.030)	(0.030)
Diploma × Left-right			−0.005			−0.005
			(0.008)			(0.009)
Diploma × Left-right : Indeterminate			0.013			−0.027*
			(0.014)			(0.015)
Age : 25 – 34	0.050	−0.030		0.128	0.021	
	(0.041)	(0.032)		(0.089)	(0.045)	
Age : 35 – 49	0.002	−0.088***		0.092	0.032	
	(0.041)	(0.029)		(0.089)	(0.045)	
Age : 50 – 64	0.009	−0.092***		0.069	−0.032	
	(0.044)	(0.029)		(0.096)	(0.049)	
Age : ≥ 65	−0.106**	−0.197***		−0.052	−0.092	
	(0.053)	(0.029)		(0.114)	(0.058)	
Income (k€/month)	−0.008			−0.018	−0.012	
	(0.008)			(0.017)	(0.009)	
Sex : Male	−0.023			0.156***	−0.004	
	(0.018)			(0.039)	(0.020)	
Size of town (1 to 5)	0.004			−0.003	0.006	
	(0.008)			(0.017)	(0.009)	
Frequency of public transit	0.016**			0.045***	0.007	
	(0.007)			(0.016)	(0.008)	
Additional covariates	✓			✓	✓	
R^2 (3,002 observations)	0.104	0.021	0.037	0.156	0.118	0.048

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Interaction term is computed using numeric variables. Omitted modalities are : *Yellow Vests : opposes*, *Left-right : Indeterminate*, *Diploma : Brevet or no diploma*, *Age : 18 – 24*. Additional covariates are defined in B.1.

Another finding is that men have a higher knowledge than women by 0.16 s.d. *ceteris paribus* (4), but their perception of the severity of CC is virtually the same (5). Finally, other characteristics have smaller or even insignificant effects.

Although the determinants we find are broadly consistent with those elicited in the literature (Upham et al., 2009; Whitmarsh, 2011; ADEME, 2018), [9] we do not encounter the political polarity which characterizes the United States. Indeed, Kahan et al. (2012) argue that American people "tend to form perceptions of societal risks that cohere with values characteristic of groups with which they identify" (this is the cultural cognition thesis), rather than through an assessment of the scientific evidence they encounter (the science comprehension thesis). It is crucial to know whether people neglect climate science in such a way, as this would mean that a media campaign would have little effect on people's assimilation of climate science. Kahan et al. (2012) and McCright & Dunlap (2011) provide evidence for cultural cognition by showing that education has little effect on perceived risk or knowledge about CC, while the interaction between education and political orientation has a significant effect. [10] We assess whether such interaction appears in the French context, by studying the interaction between the higher degree obtained and the left-right political leaning (columns 4, 6). We find no significant interaction, and obtain the same nil result when replacing the traditional left-right scale by the Yellow Vests positioning, and/or the higher degree by knowledge about CC (see Appendix J). This lack of evidence suggests that the public debate over CC is less polarized in France than in the US, [11] and that the knowledge and perception of many French people could change with better access to information over CC.

Figure 6.1 gives a sense of the shift in the perception and support for climate policies that could follow an information campaign, as it shows the correlations between attitudes over CC, climate policies, and socio-demographics. Knowledge is highly correlated with the perceived gravity of CC (correlation of 0.43), and both of these variables are in turn well correlated with the readiness to adopt an ecological lifestyle and to the number of climate policies (of Figure 5.2) supported (correlations around 0.3). The acceptance of our Tax & Dividend is less correlated with attitudes (at 0.1-0.2), as the support for this policy is already low. Still, the positive correlation between knowledge and support for other climate policies is an encouraging prospect for an information campaign about CC and even more so since we did not find evidence that partisanship would lead to the dismissal of scientific discourse. Finally, as previously seen, diploma and age are quite correlated with attitudes, though these correlations are below those between attitudes over CC and over policies, at 0 to 0.2.

6.2 Attitudes over policies

To better understand the heterogeneity in people's support, we regress several indicators of attitudes towards climate policies on respondents' characteristics. Table 6.2 reports the results for the acceptance of our Tax & Dividend (columns 1-2) and the readiness to adopt an ecological lifestyle (6) in the case that the richest were contributing, efforts were shared globally, and alternatives were developed. We also use the eight policies proposed in Figure 5.2 in our dependent variables :

9. See also Capstick et al. (2015) for trends in attitudes.

10. Funk & Kennedy (2016) also report that Republicans are equally distrustful of climate scientists' integrity whatever their level of education, while the distrust vanishes for Democrats with higher degrees. The mechanism of the interaction is documented by Ehret et al. (2018) and Van Boven et al. (2018) : people form beliefs through partisan cues, by adopting views expressed by political figures of the party they identify and rejecting positions from the other party.

11. A finding reminiscent of Ziegler (2017), who studies Germany.

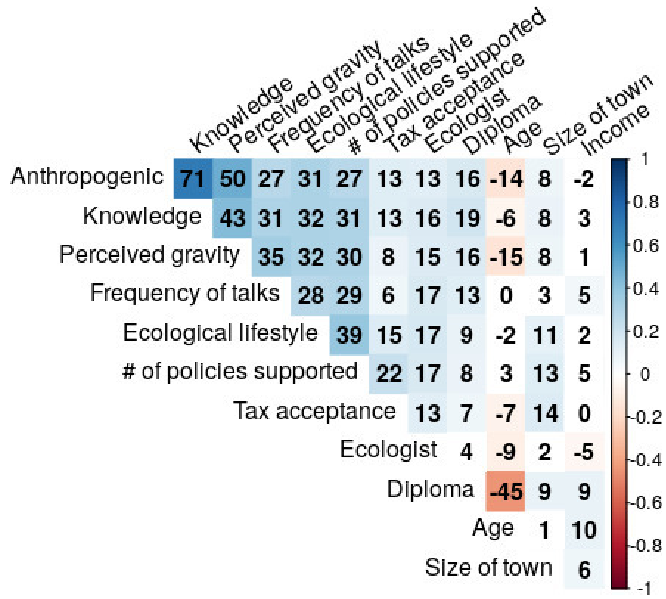


FIGURE 6.1 – Correlations between attitudes over climate change, climate policies and socio-demographics (in %).

column 3 studies the share of policies approved while column 4 features the preference for norms vs. taxes within the policies. Similarly, column 5 uses six measures of Figure 5.1 to define an index of preference for earmarking vs. transfers. Indexes for these preferences are constructed as follows :

$$\text{Norms vs. taxes} = \sum_{p \in \text{norms}} \text{score}_p - \sum_{p \in \text{taxes}} \text{score}_p \tag{6.1}$$

where the score of each measure corresponds to a grade between -2 (for a "Not at all" answer) and 2 (for "Yes, completely"). We proceed similarly for earmarking vs. transfers, and describe the categorization of measures in Appendix B.2. Again, we normalize these two indexes by subtracting the mean (2.8 for norms vs. taxes, 1.4 for earmarking vs. transfers) and dividing by the standard deviation (3.3 and 3.1 respectively). Tables G.3 and G.4 in Appendix provide the analysis of the determinants of acceptance for each of the eight policies and nine revenue recycling. The results are overall very similar to those provided by the more synthetic indicators presented here.

As suggested by the correlation matrix of section 6.1, knowledge about CC and the conviction that it would be disastrous positively affect the approval of climate policies, *ceteris paribus*. Excluding the (endogenous) variables describing political orientation, an increase in knowledge by 1 s.d. would induce a lower likelihood to reject Tax & Dividend by 5 p.p. (column 2). The effect of these variables is even stronger when considering the share of policies approved : controlling for socio-demographics, an increase in knowledge by 1 s.d. is associated with an additional approval of 6 p.p. while the conviction that CC is disastrous increases it by 9 p.p. (see Appendix I). Beyond the strong correlation we previously found, these results confirm that increasing climate awareness could significantly increase the support for climate policies.

Besides attitudes over CC, the two most critical determinants appear to be one's affiliation as an ecologist and one's position towards the Yellow Vests. All else equal, ecologists are more likely

Table 6.2 – Determinants of attitudes towards climate policies

	Acceptance of Tax & dividend		Share of policies approved	Norms vs. taxes	Earmarking vs. transfers	Ecological lifestyle
	(1)	(2)	(3)	(4)	(5)	(6)
Knowledge about CC	0.029***	0.048***	0.044***	0.024	0.131***	0.103***
	(0.009)	(0.009)	(0.005)	(0.020)	(0.020)	(0.009)
CC is disastrous	0.022	0.037**	0.081***	0.125***	0.156***	0.142***
	(0.018)	(0.018)	(0.010)	(0.040)	(0.039)	(0.018)
Interest in politics (0 to 2)	−0.019		0.034***	−0.010	0.053*	0.026**
	(0.013)		(0.007)	(0.029)	(0.028)	(0.013)
Ecologist	0.126***		0.082***	−0.134**	0.249***	0.149***
	(0.024)		(0.013)	(0.056)	(0.054)	(0.025)
Yellow Vests : PNR	−0.021		−0.052***	0.007	−0.110	−0.079**
	(0.032)		(0.018)	(0.073)	(0.071)	(0.033)
Yellow Vests : understands	−0.144***		−0.029**	−0.056	−0.091*	−0.013
	(0.022)		(0.012)	(0.050)	(0.049)	(0.022)
Yellow Vests : supports	−0.222***		−0.048***	−0.131**	−0.142***	−0.023
	(0.023)		(0.013)	(0.053)	(0.052)	(0.024)
Yellow Vests : is part	−0.214***		−0.084***	−0.252***	−0.175*	−0.037
	(0.043)		(0.023)	(0.097)	(0.095)	(0.043)
Left-right : Extreme-left	−0.040		0.025	−0.285**	0.167	0.047
	(0.056)		(0.031)	(0.127)	(0.124)	(0.056)
Left-right : Left	0.072***		−0.005	−0.137**	0.002	0.028
	(0.027)		(0.015)	(0.061)	(0.060)	(0.027)
Left-right : Center	0.051*		0.011	−0.051	0.051	0.095***
	(0.030)		(0.016)	(0.068)	(0.066)	(0.030)
Left-right : Right	−0.022		0.008	0.030	0.064	0.005
	(0.028)		(0.016)	(0.065)	(0.063)	(0.029)
Left-right : Extreme-right	−0.041		−0.028	0.055	0.009	0.014
	(0.034)		(0.018)	(0.077)	(0.075)	(0.034)
Diploma (1 to 4)	−0.006	−0.001	0.005	0.006	0.017	−0.008
	(0.009)	(0.008)	(0.005)	(0.020)	(0.020)	(0.009)
Age : 25 − 34	−0.047	−0.099***	−0.023	0.038	−0.159*	0.032
	(0.041)	(0.032)	(0.022)	(0.093)	(0.090)	(0.041)
Age : 35 − 49	−0.047	−0.089***	−0.017	0.189**	−0.002	0.039
	(0.040)	(0.030)	(0.022)	(0.092)	(0.089)	(0.041)
Age : 50 − 64	−0.054	−0.114***	−0.010	0.322***	−0.058	0.049
	(0.044)	(0.031)	(0.024)	(0.100)	(0.097)	(0.044)
Age : $\geq$ 65	−0.066	−0.100***	−0.009	0.370***	−0.056	0.008
	(0.052)	(0.032)	(0.028)	(0.118)	(0.115)	(0.052)
Income (k€/month)	0.006	0.001	0.009**	0.014	0.031*	−0.004
	(0.008)	(0.005)	(0.004)	(0.018)	(0.017)	(0.008)
Sex : Male	−0.053***	−0.074***	−0.017*	−0.028	−0.004	−0.063***
	(0.018)	(0.017)	(0.010)	(0.040)	(0.039)	(0.018)
Size of town (1 to 5)	0.019**	0.033***	0.0002	0.009	−0.003	−0.003
	(0.008)	(0.007)	(0.004)	(0.018)	(0.017)	(0.008)
Frequency of public transit	−0.003	0.014**	−0.003	0.046***	0.021	0.024***
	(0.007)	(0.006)	(0.004)	(0.017)	(0.016)	(0.007)
Additional covariates	✓		✓	✓	✓	✓
Observations	3,002	3,002	3,002	3,002	3,002	3,002
R^2	0.150	0.051	0.226	0.081	0.121	0.202

*p<0.1 ; **p<0.05 ; ***p<0.01

Note : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in B.1.

to accept Tax & Dividend by 13 p.p., and more willing to approve other environmental policies by about 8 p.p. Conversely, holding other variables constant, people supporting the Yellow Vests are 22 p.p. more likely to reject Tax & Dividend relative to those opposed to the movement. As shown in column 3, higher affinity with the Yellow Vests is also associated with less support for other climate policies. Ecologists (resp. the Yellow Vests supporters) being more (resp. less) favorable to environmental policies and spending, their relative preference for earmarking vs. transfers is higher (resp. lower) than average, while for both groups the relative preference for norms vs. taxes is lower than average. Also, ecologists' attitudes towards environmental policies translate into a higher willingness to adopt an ecological lifestyle (by 15 p.p.), but the opposite does not hold true for the Yellow Vests. Although this could signal some warm glow, [12] it also suggests that their strong rejection of environmental policies does not simply reflect lower concerns about the environment. Rather, the conditions of fairness embedded in our question could be critical for Yellow Vests to accept sacrifices. Their rejection could also reflect a deeper rejection of policies in general, due to a high distrust in the government — documented in Algan et al. (2019). This interpretation echoes the recent findings of Rafaty (2018), who shows that perceptions of corruption and political distrust negatively affect the stringency of climate policies. Finally, although the heterogeneity in responses is significant between these two groups, the ranking of the preferred option remains consistent : on average, both ecologists and supporters of the Yellow Vests favor norms over taxes and earmarking over transfers.

A parallel message from Table 6.2 is that the standard left-right spectrum is not the most relevant to understand attitudes towards environmental policies. None of our five left-right dummy variables are significantly correlated with the share of policies approved, and overall, attitudes vary much less along the left-right spectrum than along the Yellow Vests cleavage. That being said, Tax & Dividend is still significantly more supported by people from the left (+7 p.p.) and the center (+5 p.p.) than by those indeterminate. This is in line with the literature (see e.g. Bornstein & Lanz 2008; McCright et al. 2013 or Drews & van den Bergh 2016 for a review). Without controlling for other variables, we find that people that are most likely to accept the Tax & Dividend in France are the ones affiliated with the center (+9 p.p. relative to "Indeterminate"), and the least likely are those on the extreme-right (−15 p.p., see Appendix), which may be driven by their respective support or rejection of the current government who tried to increase the carbon tax. Our results also show that people from the extreme-left and the center are the most likely to approve other environmental policies (+7 p.p.), while the least likely are those on the extreme-right (−6 p.p.). Still, these differences become small and not statistically significant when covariates are included.

Besides political attitudes, we also observe heterogeneity in people's responses along socio-demographic lines. As in attitudes over CC, age plays a role, as 18-24 are about 10 p.p. more likely to accept the Tax & Dividend (column 2). Still, controlling for knowledge, political attitudes and other variables, this effect is reduced by half. Similarly, more educated people tend to be more open to environmental policies (as previously found by Thalmann, 2004), but this effect becomes insignificant once age dummies are included as covariates. Furthermore, we find little effect of income on attitudes towards climate policies, a result that confirms that of Thalmann (2004) in Switzerland. Using our full set of controls, the most significant variables differ from the main factors of attitudes over CC : these significant variables are size of town (city dwellers being more favorable to environmental policies, as in Thalmann, 2004), and sex (males being less favorable).

12. Here, "warm glow" refers to one's unintentional strategy to overestimate their virtue in order to derive satisfaction.

Although men have a higher knowledge about CC than women on average, this does not translate into higher pessimism (see section 6.1), and it even coincides with lower support for climate policies. This phenomenon is consistent with the findings of Stern et al. (1993) and Hampel et al. (1996) that women are more attentive to links between the environment and things they value, even if they share the same values and beliefs as men. Difference in perception of CC's impact on oneself could explain women's higher support for climate policies, even given a lower factual knowledge.

7 Conclusion

Despite a social movement against the carbon tax, French people appear mostly aware and concerned about climate change. Their rejection should therefore not be taken as a low willingness to act for the environment, but rather as a perceived inadequacy between current carbon taxation and the fight for the climate. Our results identify several barriers — distributive concerns, inefficacy and lack of alternatives — that could be partly alleviated with specific complementary policies. In particular, French people favor investments in green infrastructures that provide them with alternatives and foster the energy transition. They also appear willing to accept certain norms as well as Pigouvian taxes if these target specific behaviors (or populations) such as air travel. The heterogeneity in people's attitudes is significant, but the relative ranking of the different policy options are in general consistent across groups of population, suggesting the following paths towards a successful ecological transition.

First and foremost, a massive and long-lasting information campaign could be launched to improve knowledge about climate change and climate policies. Indeed, higher knowledge is clearly associated with higher concern for CC and higher support for climate policies. Second, as people mostly favor policies that provide alternatives to fossil fuels, the government could develop such policies as a substitute to a carbon tax : investments, subsidies, and regulations in favor of public transport, cleaner vehicles and thermal insulation, etc. Third, a tax and dividend restricted to kerosene could serve as a learning example as kerosene taxation is popular. [13] Last but not least, a more cost-effective carbon tax should later complement these policies, as people get convinced by the objective of carbon neutrality and by the government's commitment towards this goal.

But to successfully introduce a carbon tax, it is important to build public trust in politicians (Harring & Jagers, 2013; Rafaty, 2018) and to correct the inequities of the tax. As such, it is no surprise if political trust is among the highest in the country that first introduced a carbon tax, Sweden (Klenert et al., 2018). It is no coincidence either that the 1991 Swedish tax was part of a comprehensive restructuring of the tax system, the popular "reform of the century", resulting from a dialogue with all stakeholders (Sterner, 2014).

The French government is willing to build such a democratic consensus, as it has just launched an assembly to tackle climate change composed of 150 citizens randomly drawn. Nevertheless, it will remain challenging to reintroduce a carbon tax in the short-run, since French people's beliefs about carbon taxation are largely biased, and these biases are well anchored (as shown in our companion paper, Douenne & Fabre (2020b)). In a nutshell, market imperfections, distributive effects and political acceptability concerns all call for a combination of different types of climate policies rather than a single price signal (Stern & Stiglitz, 2017; Stiglitz, 2019). The French context seems to call for a focus on the other policies to make the carbon tax politically acceptable.

13. Murray & Rivers (2015) document an increase in the support of the carbon tax following its implementation in British Columbia.

Appendix

A Sources on GHG emissions

A.1 Carbon footprints

Plane vs. train Given that French electricity mix is decarbonized at 93% [14], the carbon footprint of highspeed train is actually more than 20 times lower than that of an interior flight of the same distance. Hence, we chose Bordeaux - Nice as our case study as the train connection makes a big detour by Paris. Thus, we obtain an emission of 10 kg of CO_2 by train as compared to 180 kg by plane. Our source for train is the French railroad company, SNCF, and is consistent with data aggregated by the official agency ADEME. For the flight, our source is a carbon footprint calculator. Another calculator provides almost the same result, so we preferred this figure rather than a higher figure from a third calculator.

Nuclear vs. wind AR5 from IPCC and Pehl et al. (2017) show that nuclear power plants and wind turbines have similar carbon footprint, at 10 gCO_2eq/kWh (for comparison, it is 500 for gas combined cycle).

Beef vs. pasta Poore & Nemecek (2018) show that median beef carbon footprint is 60 $kgCO_2eq/kg$ (more precisely, 30 $kgCO_2eq$ per 100g of protein and 200g of protein per kg) ; while the carbon footprint of wheat pasta is 1.3 $kgCO_2eq/kg$ (0.5 $kgCO_2eq$ per 1000 kcal of protein and 2695 kcal per kg). Given that a beef steak weighs 100-125g, its carbon footprint is twenty times that of two servings of pasta of 125g each.

A.2 Current and target emissions

French consumption-based yearly GHG emissions amounted in 2014 to 712 $MtCO_2eq$, i.e. 10.8 tCO_2eq p.c., and are roughly stable in recent years (CGDD, 2019). To stop climate change and stabilize the GHG concentration in the atmosphere, it is required to meet zero net emissions. To meet the Paris agreement, France National Low-Carbon Strategyaims to achieve carbon (i.e. GHG) neutrality by 2050 (CGDD, 2015). Given carbon sinks estimated at 85 Mt_2eq for 2050 (mainly forest and soil), this strategy requires reaching gross emissions of about 1 tCO_2eq p.c. at this date. Admittedly, less stringent scenarios may still allow keeping global warming below +2°C in 2100 with good probability — even considering the same burden share for France — by relying more heavily on net negative emissions after 2070 through carbon capture and storage. For this reason, we consider a range of answers as correct for the French target emission in 2050 : from 0 to 2 tCO_2eq p.c.

B Details on main regressions

B.1 Control variables

Our regression Tables 6.1 and 6.2 display only the most relevant variables, but — when specified — the following additional covariates are included as controls :

14. Cf. RTE - Bilan électrique 2018(p. 32).

Socio-demographics : *respondent's income ; household's income ; employment status* (9 categories) *; socio-professional category* (8 categories) *; region of France* (10 categories) *; household size ; number of people above 14 ; number of adults ; single ; number of c.u. ; smokes ; favored medium for news* (5 categories).

Political orientation : *conservative ; liberal ; humanist ; patriot ; apolitical.*

Energy and exposure to policies : *heating energy : gaz ; heating energy : heating oil ; accomodation size ; annual distance travelled by car ; fuel economy ; type of fuel : diesel ; type of fuel : gasoline ; number of vehicles ; simulated net gain from Tax & Dividend ; opinion on public transports ; mode of commuting transport.*

B.2 Measures for relative preferences

We constructed the two indexes of section 6.2 using the following measures :

Norms : *insulation standards ; pollution standards ; roadworthiness standards ; prohibition of polluting vehicles.*

Taxes : *kerosene ; red meat ; urban tolls ; climate fund.*

Earmarking : *renovation ; renewables ; non-polluting transport.*

Transfers : *to bottom half ; to all ; to constrained households.*

C Questionnaire

Hereafter, we only describe questions of the survey that are used in the present paper. The other questions are described and analyzed in our companion paper (Douenne & Fabre, 2020b). Words that appear in bold were actually in both bold and underlined in the respondents' questionnaire.

Socio-demographics

1. What is your postal code ?
2. What is your gender (in the sense of civil status) ?
   Female ; Male
3. What is your age group ?
   18 to 24 years old ; 25 to 34 years old ; 35 to 49 years old ; 50 to 64 years old ; 65 years old or more
4. What is your employment status ?
   Permanent ; Temporary contract ; Unemployed ; Student ; Retired ; Other active ; Inactive
5. What is your socio-professional category ? (Remember that the unemployed are active workers).
   Farmer ; Craftsperson, merchant ; Independent ; Executive ; Intermediate occupation ; Employee ; Worker ; Retired ; Other Inactive

6. What is your highest degree ?
   No diploma ; Brevet des collèges ; CAP or BEP [secondary] ; Baccalaureate ; Bac +2 (BTS, DUT, DEUG, schools of health and social training...) ; Bac +3 (licence...) [bachelor] ; Bac +5 or more (master, engineering or business school, doctorate, medicine, master, DEA, DESS...)
7. How many people live in your household ? Household includes : you, your family members who live with you, and your dependents.
8. What is your net **monthly** income (in euros) ? **All income** (before withholding tax) is included here : salaries, pensions, allowances, APL [housing allowance], land income, etc.
9. What is the net **monthly** income (in euros) **of your household** ? **All income** (before withholding tax) is included here : salaries, pensions, allowances, APL [housing allowance], land income, etc.
10. In your household how many people are 14 years old or older (**including yourself**) ?
11. In your household, how many people are over the age of majority (**including yourself**) ?

Energy characteristics

12. What is the surface area of your home ? (in m^2)
13. What is the heating system in your home ?
    Individual heating ; Collective heating ; PNR (Don't know, don't say)
14. What is the main heating energy source in your home ?
    Electricity Town gas ; Butane, propane, tank gas ; Heating oil ; Wood, solar, geothermal, aerothermal (heat pump) ; Other ; PNR (Don't know, don't say)
15. How many motor vehicles does your household have ?
    None ; One ; Two or more
16. [Without a vehicle] How many kilometers have you driven in the last 12 months ?
17. [One vehicle] What type of fuel do you use for this vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
18. [One vehicle] What is the average fuel economy of your vehicle ? (in Liters per 100 km)
19. [One vehicle] How many kilometers have you driven with your vehicle in the last 12 months ?
20. [At least two vehicles] What type of fuel do you use for your main vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
21. [At least two vehicles] What type of fuel do you use for your second vehicle ?
    Electric or hybrid ; Diesel ; Gasoline ; Other
22. [At least two vehicles] What is the average fuel economy of all your vehicles ? (in Liters per 100 km)
23. [At least two vehicles] How many kilometers have you driven with all your vehicles in the last 12 months ?

Partial reforms [transport / housing] (...)

24. If fuel prices increased by 50 cents per liter, by how much would **your household** reduce its fuel consumption ?
    0% - [*I already consume almost none / I am already not consuming*] *; 0%* - [*I am constrained*

on all my trips / I will not reduce it] ; From 0% to 10% ; From 10% to 20% ; From 20% to 30% ; More than 30% - [I would change my travel habits significantly / I would change my consumption significantly]

25. In your opinion, if [fuel prices increased by 50 cents per liter / gas and heating oil prices increased by 30%], by how much would **French people** reduce their consumption on average ?
From 0% to 3% ; From 3% to 10% ; From 3% to 10% ; From 10% to 20% ; From 20% to 30% ; More than 30%

Tax & Dividend : initial

26. The government is studying an increase in the carbon tax, whose revenues would be redistributed to all households, regardless of their income. This would imply :
    - an increase in the price of gasoline by 11 cents per liter and diesel by 13 cents per liter ;
    - an increase of 13% in the price of gas, and 15% in the price of heating oil ;
    - an annual payment of 110€ to each adult, or 220€ per year for a couple.

    (...)
27. [[empty] / Scientists agree that a carbon tax would be effective in reducing pollution.] Do you think that such a measure would reduce pollution and fight climate change ?
Yes ; No ; PNR (Don't know, don't say)
28. In your opinion, which categories would lose [[blank] / purchasing power] with such a measure ? (Several answers possible)
No one ; The poorest ; The middle classes ; The richest ; All French people ; Rural or peri-urban people ; Some French people, but not a particular income category ; PNR (Don't know, don't say)
29. In your opinion, what categories would gain purchasing power with such a measure ? (Several answers possible)
No one ; The poorest ; The middle classes ; The richest ; All French people ; Urban dwellers ; Some French people, but not a particular income category ; PNR (Don't know, don't say)

Tax & Dividend : after knowledge We always consider the same measure. (...)

30. Why do you think this measure is beneficial ? (Maximum three responses)
Contributes to the fight climate change ; Reduces the harmful effects of pollution on health ; Reduces traffic congestion ; Increases my purchasing power ; Increases the purchasing power of the poorest ; Fosters France's independence from fossil energy imports ; Prepares the economy for tomorrow's challenges ; For none of these reasons ; Other (specify) :
31. Why do you think this measure is unwanted ? (Maximum three answers)
Is ineffective in reducing pollution ; Alternatives are insufficient or too expensive ; Penalizes rural areas ; Decreases my purchasing power ; Decreases the purchasing power of some modest households ; Harms the economy and employment ; Is a pretext for raising taxes ; For none of these reasons ; Other (specify) :

(...)

Attitudes over other policies

32. In which cases would you be in favor of increasing the carbon tax ? I would be in favor if the tax revenues were used to finance...
    (a) a payment to the 50% poorest French people (those earning less than 1670€ per month)
    (b) a payment to all French people
    (c) a compensation for households forced to consume petroleum products
    (d) a decrease in social contributions
    (e) a decrease in VAT
    (f) a decrease in the public deficit
    (g) the thermal renovation of buildings
    (h) renewable energy (wind, solar, etc.)
    (i) clean transport

Yes, absolutely ; Yes, rather ; Indifferent or Don't know ; No, not really ; No, not at all

33. Please select "A little" (test to check that you are attentive).
    Not at all ; A little ; A lot ; Completely ; PNR (Don't know, don't say)
34. Would you support the following environmental policies ?
    (a) A tax on kerosene (aviation)
    (b) A tax on red meat
    (c) Stricter standards on the insulation of new buildings
    (d) Stricter standards on the pollution of new vehicles
    (e) Stricter standards on pollution during roadworthiness tests
    (f) The prohibition of polluting vehicles in city centers
    (g) The introduction of urban tolls
    (h) A contribution to a global climate fund

Yes, absolutely ; Yes, rather ; Indifferent or Don't know ; No, not really ; No, not at all

35. For historical reasons, diesel is taxed less than gasoline. Would you be in favor of raising taxes on diesel to catch up with the level of taxation on gasoline ?
    Yes ; No ; PNR (Don't know, don't say)

Attitudes over climate change

36. How often do you talk about climate change ?
    Several times a month ; Several times a year ; Almost never ; PNR (Don't know, don't say)
37. In your opinion, climate change...
    is not a reality ; is mainly due to natural climate variability ; is mainly due to human activity ; PNR (Don't know, don't say).
38. Which of the following elements contribute to global warming ? (Several answers possible)
    CO_2 *; Methane ; Oxygen ; Particulate matter*

39. In your opinion, which of the following statements are true ? (Several answers possible).
Consuming one beef steak emits about 20 times more greenhouse gases than eating two servings of pasta. ; Electricity produced by nuclear power emits about 20 times more greenhouse gases than electricity produced by wind turbines. ; A seat in a Bordeaux - Nice journey emits about 20 times more greenhouse gases by plane than by high speed train.
40. In your opinion, how would the effects of climate change be, if humanity did nothing to limit it ?
Insignificant, or even beneficial ; Small, because humans would be able to live with it ; Grave, because there would be more natural disasters ; Disastrous, lifestyles would be largely altered ; Cataclysmic, humankind would disappear ; PNR(Don't know, don't say)
41. In which of these two regions do you think will climate change have the worst consequences ?
The European Union ; India ; As much in both
42. In your opinion, in France, which generations will be seriously affected by climate change ? (Several answers possible)
People born in the 1960s ; People born in the 1990s ; People born in the 2020s ; People born in the 2050s ; None of the four
43. In your opinion, who is responsible for climate change ? (Several possible choices)
Each of us ; The richest ; Governments ; Some foreign countries ; Past generations ; Natural causes
44. Currently, each French person emits on average the equivalent of 10 tons of CO_2 per year.

   In your opinion, how much must this figure be reduced to by 2050 in order to hope to contain global warming to +2°C in 2100 (if all countries did the same) ? In 2050, we should emit at most...
   0 ; 1 ; 2 ; 3 ; 4 ; 5 ; 6 ; 7 ; 8 ; 9 ; 10 tons
45. Has climate change had or will it have an influence on your decision to make a child (or children) ?
Yes ; No ; PNR (Don't know, don't say)
46. [If *Yes*] Why does climate change influence your decision to have a child (or children) ? (Several answers possible).
Because I don't want my child to live in a devastated world. ; Because each additional human being aggravates climate change.
47. Would you be willing to change your lifestyle to fight climate change ? (Several answers possible)
Yes, if policies went in this direction ; Yes, if I had the financial means ; Yes, if everyone did the same ; No, only the richest people have to change their way of life ; No, it is against my personal interest ; No, I think climate change is not a real problem ; I have already adopted a sustainable way of life ; I try, but I have trouble changing my habits
48. Assuming that all states in the world agree to firmly fight climate change, notably through a transition to renewable energy, by making the richest contribute, and imagining that France would expand the supply of non-polluting transport very widely ; would you be willing to adopt an ecological lifestyle (i.e. eat little red meat and ensure to use almost no gasoline, diesel or kerosene) ?
Yes ; No ; PNR (Don't know, don't say)

Access to public transport and mobility habits

49. How many minutes walk is it to the nearest public transit stop ? (To simplify, you can use the conversion 1 km = 10 min walk).
in min : ; *PNR (Don't know, don't say)*
50. How often does the nearest public transport pass ? (excluding school buses)
Less than three times a day ; Between four times a day and once an hour ; Once or twice an hour ; More than three times an hour ; PNR (Don't know, don't say)
51. What do you think about the availability of public transport where you live ? It is...
Satisfactory ; Suitable, but should be increased ; Limited, but sufficient ; Insufficient ; PNR (Don't know, don't say)
52. What mode of transportation do you mainly use for each of the following trips ?
    (a) Home - work (or studies)
    (b) Grocery shopping
    (c) Leisure (excluding holidays)

Car ; Public transport ; Walking or cycling ; Two-wheeled vehicle ; Carpooling ; Not concerned

53. [If *Car* selected for Work] Would it be possible for you, without changing your home or workplace, to travel from home to work using public transport ?
Yes, it would not be very difficult for me ; Yes, but it would bother me ; No ; PNR (Don't know, don't say)
54. [If *Car* selected for Work] Would it be possible for you, without changing your home or workplace, to travel from home to work by walking or cycling ?
Yes, it would not be very difficult for me ; Yes, but it would bother me ; No ; PNR (Don't know, don't say)

Politics and media

55. How much are you interested in politics ?
Almost not ; A little ; A lot
56. How would you define yourself ? (Several answers possible)
Extreme left ; Left ; Center ; Right ; Extreme right ; Liberal ; Conservative ; Humanist ; Patriot ; Apolitical ; Ecologist
57. How do you keep yourself informed of current events ? Mainly through...
Television ; Press (written or online) ; Social networks ; Radio ; Other
58. What do you think of the Yellow Vests ? (Several answers possible)
I am part of them ; I support them ; I understand them ; I oppose them ; PNR (Don't know, don't say)

Open field

59. The survey is nearing completion. You can now enter any comments, comments or suggestions in the field below.

D Additional results on attitudes over climate change

D.1 Perceptions

The looming threat of CC already seems to impact people's behavior. Indeed, 20% say the CC "has had or will have an influence in their decision to have a child". Among them, 37% justify it "because each additional human aggravates climate change", and 86% because they "don't want [their] child to live in a devastated world". This result echoes a survey from ADEME (2018) which shows that 63% of French people think that "living conditions will be extremely harsh" in France in 50 years and that 57% do not think CC "will be limited to acceptable levels by the end of the century". Such concern is not limited to France, as Funk & Kennedy (2016) document that 75% of American are concerned by CC. Nor is it recent, as Eurobarometer surveys cited by Whitmarsh & Capstick (2018) found that more than three-quarters of respondents were already worried about climate change in 1988, rising to almost nine in ten by 1992.

Despite — or perhaps due to — widespread hopelessness, 34% almost never talk about CC (Figure D.1). 27% talk about CC several times per month, which can give a sense of the share of people who regularly engage in long-term thinking. The relatively low amount of discussion around an issue largely perceived as a serious threat may be understood as a way to flee from one's moral duty and to protect one's lifestyle. Indeed, as a recent literature has shown, people tend to discard information perceived as bad news and display what Sharot et al. (2011) call "unrealistic optimism in front of reality". Whitmarsh & Capstick (2018) relate another strategy of avoidance : the general tendency to discount one's own contribution to causing CC and identify causes of CC primarily with other people or countries.

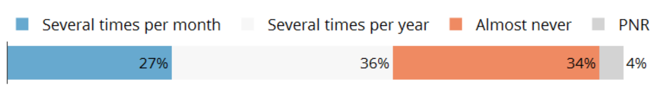


FIGURE D.1 – Frequency at which respondents talk about climate change.

One can wonder if this blindness to the causes is mirrored by a sentiment that oneself will not be impacted. This does not seem to be the case on a spatial dimension. Indeed, Figure D.2 shows that although five times more people (correctly [15]) believe that India will face more serious climate impacts than the European Union, 65% still think that both regions will face as much damage. Yet, the evidence is mild regarding the time dimension, as 45% of American think that "global warming will pose a serious threat to [them] or [their] way of life in [their] lifetime" (Gallup, 2019)while 62% of French people think that the first generation seriously affected by CC is yet to be born (Figure D.3). [16] Interestingly, a delay of one generation as the first (perceived as) affected by CC is significantly associated with a lower knowledge index by 0.1 standard deviation. This finding may

15. See e.g. vulnerability indexes (Climate Vulnerable Forum, 2012; Guillaumont, 2015; Closset et al., 2018).
16. We assume here that both countries are comparable.

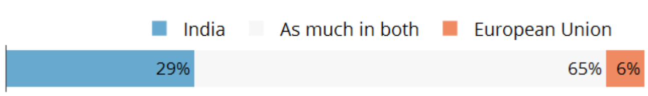


FIGURE D.2 – Perceived region where climate change impacts will be the most serious.

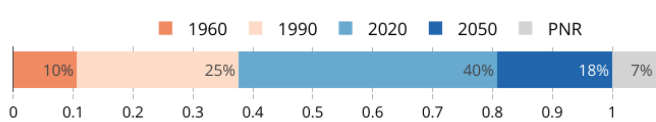


FIGURE D.3 – Perceived date of birth of first generation severely affected by CC.

indicate that learning is partly motivated by perceived personal prejudice.

D.2 The Reaction Needed

Kallbekken & Aasen (2010) report that "a poll of 22,000 respondents from 21 countries found that 83% say it will be necessary to make lifestyle and behavioural changes to reduce emissions of greenhouse gases (Globescan and PIPA, 2007)." Other French representative surveys find similar results for the reaction needed and indicate which efforts people are most ready to make. BVA (2011)indicates that, to save energy, 76% plan to "change their consumption habits" and 61% plan works in their accomodation. In the U.S., 52% already think they "do a good job at protecting the environment" Gallup (2019). However, ADEME (2018) shows that the efforts people are making or could easily make are also the least efficient to reduce GhG emissions : most people cite waste sorting (89%) or buying seasonal vegetables (87%), but fewer mention walking or cycling (55%) or using public transport (49%) instead of driving.

Logically, 62% thus think that "only legislative constraint is effective in making a successful transition and forcing everyone to change their consumption habits" (OpinionWay, 2019). The extent to which people support such legislation is documented by Bréchon et al. (2019) : 50% favor the protection of the environment at the expense of the economy and employment. In the U.S., Gallupsurveys show that this prioritization depends largely on the economic conditions, in accordance with Brulle et al. (2012) and Shum (2012) : the figure is 65% in 2019 but was 38% in 2010.

E Test different wording for winners and losers

Table E.1 – Effect of defining winners/losers in terms of purchasing power

	Dependent variable :			
	Poors expected to win (1)	City dwellers expected to win (2)	Rich expected to lose (3)	Rural expected to lose (4)
Constant	0.058***	0.207***	0.009***	0.352***
	(0.007)	(0.010)	(0.003)	(0.012)
In purchasing power	0.045***	−0.029**	0.015***	−0.014
	(0.010)	(0.014)	(0.005)	(0.017)
Observations	3,002	3,002	3,002	3,002
R^2	0.007	0.001	0.003	0.0002

*p<0.1 ; **p<0.05 ; ***p<0.01

F Who are the Yellow Vests

TABLE F.1 – Positioning towards Yellow Vests, per category.

	Opposed	Understands	Supports	Is part	PNR
Extreme-left (2%)	6%	26%	51%	12%	5%
Left (20%)	17%	36%	36%	5%	7%
Center (13%)	49%	30%	15%	2%	6%
Right (16%)	40%	32%	20%	3%	6%
Extreme-right (9%)	11%	28%	47%	10%	5%
Indeterminate (40%)	19%	32%	30%	4%	13%
Liberal (5%)	48%	26%	18%	2%	6%
Conservative (2%)	22%	28%	30%	10%	11%
Humanist (11%)	21%	35%	29%	5%	10%
Patriot (8%)	21%	27%	39%	7%	6%
Apolitical (21%)	21%	31%	32%	4%	12%
Ecologist (15%)	17%	39%	27%	5%	12%
Rural (21%)	20%	31%	34%	6%	9%
$<$20k (17%)	24%	28%	34%	6%	9%
20-100k (14%)	22%	33%	32%	4%	9%
$>$100k (31%)	29%	34%	26%	3%	8%
Paris (17%)	28%	33%	25%	4%	11%
No diploma or *Brevet* (30%)	21%	29%	34%	5%	10%
CAP or *BEP* (24%)	23%	28%	36%	6%	7%
Baccalauréat (17%)	22%	35%	29%	4%	11%
Higher (29%)	32%	21%	36%	3%	8%
Age : 18–24 (12%)	23%	34%	27%	4%	12%
Age : 25–34 (15%)	21%	33%	28%	7%	11%
Age : 35–49 (24%)	25%	32%	29%	5%	9%
Age : 50–64 (24%)	21%	32%	36%	4%	7%
Age : $\geq$ 65 (25%)	32%	30%	28%	3%	7%
Income decile : 1	25%	33%	26%	3%	14%
Income decile : 2	18%	31%	35%	5%	11%
Income decile : 3	17%	31%	32%	7%	12%
Income decile : 4	15%	33%	37%	6%	9%
Income decile : 5	21%	29%	36%	5%	8%
Income decile : 6	26%	33%	29%	6%	7%
Income decile : 7	25%	36%	28%	4%	7%
Income decile : 8	31%	31%	28%	3%	8%
Income decile : 9	39%	32%	20%	3%	6%
Income decile : 10	47%	29%	15%	3%	6%
Female (52%)	21%	34%	29%	5%	12%
Male (48%)	29%	30%	31%	5%	6%
Average	*25%*	*32%*	*30%*	*5%*	*9%*

NOTE : The percentages in parentheses express the weighted share of each category from our sample.

G Additional specifications for determinants of attitudes

Table G.1 – Determinants of attitudes towards diesel taxation

	Acceptance increase in diesel taxation			
	(1)	(2)	(3)	(4)
Knowledge on CC	0.046***			
	(0.008)			
Ecologist	0.082***			
	(0.023)			
Yellow Vests : PNR	−0.041		−0.068**	
	(0.030)		(0.034)	
Yellow Vests : understands	−0.099***		−0.134***	
	(0.021)		(0.023)	
Yellow Vests : supports	−0.188***		−0.289***	
	(0.022)		(0.024)	
Yellow Vests : is part	−0.163***		−0.300***	
	(0.040)		(0.045)	
Left-right : Extreme-left	0.082			0.076
	(0.052)			(0.060)
Left-right : Left	0.033			0.025
	(0.025)			(0.024)
Left-right : Center	0.016			0.081***
	(0.028)			(0.029)
Left-right : Right	−0.045*			−0.060**
	(0.027)			(0.026)
Left-right : Extreme-right	−0.030			−0.180***
	(0.031)			(0.033)
Size of town : -20k	−0.001	0.002		
	(0.025)	(0.025)		
Size of town : 20-100k	0.013	0.016		
	(0.027)	(0.027)		
Size of town : +100k	0.068***	0.106***		
	(0.025)	(0.022)		
Size of town : Paris	0.083**	0.143***		
	(0.041)	(0.026)		
Diesel	−0.371***	−0.474***		
	(0.023)	(0.016)		
Gasoline	0.153***			
	(0.022)			
Number vehicles	−0.022			
	(0.019)			
Additional covariates	✓			
Observations	3,002	3,002	3,002	3,002
R^2	0.357	0.271	0.054	0.018

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Note : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in Appendix C.

TABLE G.2 – Determinants of attitudes towards carbon tax revenue recycling

	Non-polluting transports	VAT cut	Renewable energies	Renovation of buildings	Transfer constrained hh.	Reduction soc. contri.	Transfer poor hh.	Reduction pub. deficit	Transfer all hh.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Knowledge on CC	0.127***	−0.050*	0.132***	0.099***	0.051*	−0.064**	−0.027	−0.009	−0.074**
	(0.025)	(0.026)	(0.025)	(0.025)	(0.026)	(0.026)	(0.029)	(0.026)	(0.029)
CC is disastrous	0.298***	0.085	0.275***	0.247***	0.151***	0.109**	0.102*	0.105**	0.078
	(0.049)	(0.052)	(0.050)	(0.049)	(0.052)	(0.053)	(0.057)	(0.052)	(0.057)
Interest in politics (0 to 2)	0.031	−0.115***	−0.003	−0.008	−0.006	−0.096**	−0.073*	−0.079**	−0.068*
	(0.035)	(0.038)	(0.036)	(0.036)	(0.038)	(0.038)	(0.041)	(0.038)	(0.041)
Ecologist	0.310***	−0.036	0.436***	0.262***	0.055	−0.085	0.183**	−0.024	−0.012
	(0.068)	(0.073)	(0.069)	(0.068)	(0.072)	(0.073)	(0.078)	(0.072)	(0.079)
Yellow Vests : PNR	−0.156*	−0.041	−0.256***	−0.171*	−0.140	−0.189**	0.032	−0.318***	−0.129
	(0.089)	(0.096)	(0.091)	(0.090)	(0.095)	(0.096)	(0.104)	(0.095)	(0.104)
Yellow Vests : understands	−0.039	0.262***	−0.106*	−0.016	0.091	0.007	0.127*	−0.096	−0.094
	(0.061)	(0.066)	(0.062)	(0.061)	(0.065)	(0.066)	(0.071)	(0.065)	(0.071)
Yellow Vests : supports	−0.271***	0.141**	−0.346***	−0.243***	−0.098	−0.166**	−0.043	−0.321***	−0.277***
	(0.065)	(0.070)	(0.066)	(0.065)	(0.069)	(0.070)	(0.076)	(0.069)	(0.076)
Yellow Vests : is part	−0.306***	0.272**	−0.370***	−0.211*	0.022	−0.112	−0.023	−0.297**	−0.345**
	(0.118)	(0.127)	(0.120)	(0.119)	(0.126)	(0.127)	(0.137)	(0.125)	(0.137)
Left-right : Extreme-left	0.066	0.162	0.066	0.223	0.043	−0.195	0.180	−0.216	−0.399**
	(0.154)	(0.166)	(0.157)	(0.155)	(0.164)	(0.166)	(0.179)	(0.164)	(0.179)
Left-right : Left	0.085	−0.079	0.145*	0.089	0.074	−0.097	0.301***	−0.099	−0.065
	(0.074)	(0.080)	(0.076)	(0.075)	(0.079)	(0.080)	(0.086)	(0.079)	(0.087)
Left-right : Center	0.038	−0.162*	0.021	0.137*	0.083	−0.093	0.054	0.105	−0.100
	(0.082)	(0.088)	(0.084)	(0.083)	(0.087)	(0.089)	(0.095)	(0.087)	(0.096)
Left-right : Right	0.048	−0.013	0.058	0.084	0.072	0.090	−0.134	0.160*	0.051
	(0.079)	(0.085)	(0.080)	(0.079)	(0.084)	(0.085)	(0.092)	(0.084)	(0.092)
Left-right : Extreme-right	−0.212**	−0.041	−0.106	−0.147	−0.186*	−0.013	−0.209*	−0.172*	−0.095
	(0.093)	(0.100)	(0.095)	(0.094)	(0.099)	(0.100)	(0.108)	(0.099)	(0.108)
Diploma (1 to 4)	−0.014	−0.027	0.016	0.002	−0.014	−0.047*	−0.046	−0.021	0.011
	(0.025)	(0.026)	(0.025)	(0.025)	(0.026)	(0.027)	(0.029)	(0.026)	(0.029)
Age : 25 – 34	−0.285**	−0.105	−0.270**	−0.101	−0.096	−0.120	−0.308**	−0.261**	0.244*
	(0.113)	(0.121)	(0.115)	(0.113)	(0.120)	(0.121)	(0.131)	(0.120)	(0.131)
Age : 35 – 49	−0.167	−0.083	−0.109	0.057	−0.023	0.014	−0.283**	−0.202*	0.096
	(0.112)	(0.120)	(0.114)	(0.112)	(0.119)	(0.120)	(0.130)	(0.119)	(0.130)
Age : 50 – 64	−0.015	0.032	−0.038	0.122	0.178	0.166	−0.053	−0.176	0.129
	(0.121)	(0.130)	(0.124)	(0.122)	(0.129)	(0.131)	(0.141)	(0.129)	(0.141)
Age : $\geq$ 65	−0.010	−0.034	−0.034	0.217	0.215	0.130	0.028	−0.140	0.111
	(0.143)	(0.154)	(0.146)	(0.144)	(0.152)	(0.154)	(0.166)	(0.152)	(0.166)
Income (k€/month)	0.025	−0.016	0.014	0.013	−0.014	−0.002	−0.084***	0.008	0.054**
	(0.022)	(0.023)	(0.022)	(0.022)	(0.023)	(0.023)	(0.025)	(0.023)	(0.025)
Sex : Male	−0.151***	−0.183***	−0.183***	−0.132***	−0.190***	−0.221***	−0.161***	−0.132**	−0.108*
	(0.049)	(0.053)	(0.050)	(0.049)	(0.052)	(0.053)	(0.057)	(0.052)	(0.057)
Size of town (1 to 5)	−0.007	0.005	0.004	0.003	−0.012	0.019	0.029	0.016	−0.007
	(0.021)	(0.023)	(0.022)	(0.021)	(0.023)	(0.023)	(0.025)	(0.023)	(0.025)
Frequency of public transit	0.025	−0.026	−0.006	0.0001	−0.012	−0.015	−0.019	−0.029	−0.014
	(0.020)	(0.022)	(0.021)	(0.021)	(0.022)	(0.022)	(0.024)	(0.022)	(0.024)
Additional covariates	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	3,002	3,002	3,002	3,002	3,002	3,002	3,002	3,002	3,002
R^2	0.125	0.066	0.129	0.095	0.060	0.058	0.120	0.053	0.064

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in Appendix C.

Table G.3 – Determinants of attitudes towards specific climate policies

	Norms for buildings	Norms for new vehicles	Tax on kerosene	Prohibition pol. vehicles	Norms for old vehicles	Contribution climate fund	Tax on red meat	Urban tolls
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Knowledge on CC	0.155***	0.186***	0.130***	0.118***	0.100***	0.187***	0.118***	0.027
	(0.022)	(0.022)	(0.024)	(0.025)	(0.024)	(0.025)	(0.023)	(0.023)
CC is disastrous	0.175***	0.360***	0.105**	0.246***	0.252***	0.271***	0.160***	0.092**
	(0.043)	(0.043)	(0.047)	(0.050)	(0.047)	(0.050)	(0.046)	(0.046)
Interest in politics (0 to 2)	0.117***	0.115***	0.245***	0.022	0.003	0.041	−0.022	0.027
	(0.031)	(0.031)	(0.034)	(0.036)	(0.034)	(0.036)	(0.033)	(0.033)
Ecologist	0.141**	0.160***	0.263***	0.317***	0.233***	0.288***	0.480***	0.267***
	(0.059)	(0.059)	(0.065)	(0.069)	(0.066)	(0.069)	(0.063)	(0.064)
Yellow Vests : PNR	−0.151*	−0.084	−0.203**	−0.104	−0.127	−0.086	0.012	−0.213**
	(0.078)	(0.078)	(0.086)	(0.091)	(0.087)	(0.091)	(0.083)	(0.084)
Yellow Vests : understands	−0.005	−0.103*	0.041	−0.162***	−0.139**	−0.113*	0.069	−0.224***
	(0.053)	(0.053)	(0.059)	(0.062)	(0.059)	(0.062)	(0.057)	(0.058)
Yellow Vests : supports	−0.071	−0.178***	0.201***	−0.285***	−0.294***	−0.291***	0.059	−0.365***
	(0.057)	(0.057)	(0.062)	(0.066)	(0.063)	(0.066)	(0.061)	(0.061)
Yellow Vests : is part	−0.147	−0.447***	0.171	−0.573***	−0.456***	−0.536***	−0.107	−0.324***
	(0.104)	(0.103)	(0.113)	(0.121)	(0.115)	(0.120)	(0.111)	(0.112)
Left-right : Extreme-left	−0.076	−0.174	0.007	−0.191	−0.051	0.267*	0.199	−0.017
	(0.135)	(0.135)	(0.148)	(0.157)	(0.150)	(0.157)	(0.144)	(0.146)
Left-right : Left	0.009	−0.067	−0.070	−0.084	−0.110	0.226***	−0.007	0.056
	(0.065)	(0.065)	(0.071)	(0.076)	(0.072)	(0.076)	(0.070)	(0.070)
Left-right : Center	0.062	−0.017	0.111	−0.043	0.029	−0.047	0.028	0.110
	(0.072)	(0.072)	(0.079)	(0.084)	(0.080)	(0.084)	(0.077)	(0.078)
Left-right : Right	−0.046	−0.036	−0.048	−0.021	0.003	−0.047	−0.114	0.009
	(0.069)	(0.069)	(0.076)	(0.080)	(0.077)	(0.080)	(0.074)	(0.074)
Left-right : Extreme-right	−0.013	−0.064	0.007	−0.215**	−0.262***	−0.329***	−0.236***	−0.180**
	(0.082)	(0.082)	(0.089)	(0.095)	(0.090)	(0.095)	(0.087)	(0.088)
Diploma (1 to 4)	−0.030	−0.003	0.017	0.044*	0.015	−0.037	0.011	0.016
	(0.022)	(0.022)	(0.024)	(0.025)	(0.024)	(0.025)	(0.023)	(0.023)
Age : 25 – 34	−0.012	−0.066	0.223**	0.051	−0.015	−0.174	−0.199*	−0.016
	(0.099)	(0.099)	(0.108)	(0.115)	(0.109)	(0.115)	(0.105)	(0.106)
Age : 35 – 49	−0.014	0.087	0.319***	0.130	−0.060	−0.227**	−0.419***	−0.155
	(0.098)	(0.098)	(0.107)	(0.114)	(0.109)	(0.114)	(0.105)	(0.106)
Age : 50 – 64	0.096	0.145	0.427***	0.173	0.090	−0.368***	−0.423***	−0.199*
	(0.106)	(0.106)	(0.116)	(0.124)	(0.118)	(0.123)	(0.113)	(0.114)
Age : $\geq$ 65	0.080	0.123	0.447***	0.275*	0.210	−0.483***	−0.394***	−0.109
	(0.125)	(0.125)	(0.137)	(0.146)	(0.139)	(0.145)	(0.134)	(0.135)
Income (k€/month)	0.029	0.004	−0.025	0.040*	0.038*	0.039*	0.004	0.046**
	(0.019)	(0.019)	(0.021)	(0.022)	(0.021)	(0.022)	(0.020)	(0.020)
Sex : Male	−0.120***	−0.114***	0.057	−0.026	−0.132***	−0.216***	−0.136***	−0.002
	(0.043)	(0.043)	(0.047)	(0.050)	(0.047)	(0.050)	(0.046)	(0.046)
Size of town (1 to 5)	0.003	0.004	−0.041**	0.020	0.018	0.038*	0.049**	−0.029
	(0.019)	(0.019)	(0.020)	(0.022)	(0.021)	(0.022)	(0.020)	(0.020)
Frequency of public transit	0.013	0.002	−0.040**	−0.028	−0.002	−0.040*	−0.052***	−0.036*
	(0.018)	(0.018)	(0.020)	(0.021)	(0.020)	(0.021)	(0.019)	(0.019)
Additional covariates	✓	✓	✓	✓	✓	✓	✓	✓
Observations	3,002	3,002	3,002	3,002	3,002	3,002	3,002	3,002
R^2	0.086	0.165	0.117	0.164	0.176	0.173	0.147	0.118

*p<0.1 ; **p<0.05 ; ***p<0.01

Note : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in Appendix C.

TABLE G.4 – Determinants of attitudes towards climate policies, additional specifications

	Share of policies	Tax & dividend	
	(1)	(2)	(3)
Knowledge on CC	0.057***		
	(0.005)		
CC is disastrous	0.090***		
	(0.010)		
Diploma (1 to 4)	0.006		
	(0.004)		
Age : 25 – 34	−0.039**		
	(0.018)		
Age : 35 – 49	−0.019		
	(0.017)		
Age : 50 – 64	0.005		
	(0.017)		
Age : ≥ 65	0.045**		
	(0.018)		
Income (k€/month)	0.003		
	(0.002)		
Sex : Male	−0.008		
	(0.009)		
Size of town (1 to 5)	0.008**		
	(0.004)		
Frequency of public transit	0.017***		
	(0.004)		
Left-right : Extreme-left		0.072**	−0.065
		(0.033)	(0.057)
Left-right : Left		0.040***	0.031
		(0.013)	(0.022)
Left-right : Center		0.071***	0.090***
		(0.015)	(0.026)
Left-right : Right		0.029**	−0.037
		(0.014)	(0.024)
Left-right : Extreme-right		−0.061***	−0.155***
		(0.018)	(0.031)
Observations	3,002	3,002	3,002
R^2	0.143	0.018	0.017

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in Appendix C.

H Construction of the knowledge index

We synthesize the different dimensions of knowledge proposed by Kiel & Rost (2002) and summarized by Hoppe et al. (2018) using our questions on the existence and anthropogenic origin of CC (corresponding to the causal knowledge), on the region most affected (effects), as well as our scores on the emission target (basic), greenhouse gases (basic) and on activities responsible for CC (action-related).

From an exploratory factor analysis (fitted using the maximum likelihood method), we find the factor which explains the highest share of common variance, and report it in Table H.1. We use the factor loadings hereby obtained to define the relative weights of the components of our index of knowledge, and we round them for readability purpose. The rounding has virtually no effect on the result, as the correlation between our index and the factor obtained is 0.999. For information, the correlations between the different components of our index, including our index itself, are reported on Figure H.1.

Moreover, Table H.2 shows that the determinants of Tax & Dividend are robust to the choice of the *knowledge* variable : if we replace our index by any of its component, the coefficients of the other determinants are virtually unchanged. Interestingly, this analysis indicates that it is the knowledge on the existence and the anthropogenic nature of CC that drives the effect of overall knowledge, justifying a higher weight for these two components. Finally, we could reproduce this robustness check for the other dependent variable of Table II, and also by replacing the independent variable *knowledge* in Table I, and we would again see that the other coefficients are essentially unaffected.

TABLE H.1 – Factor loadings and weights chosen for different dimensions of knowledge on CC

Variable	GhG	Activities	Exists	Anthropogenic	Target	Region
Loading	.212	.182	.398	.601	.200	.000
Weight	1	1	2	3	1	0

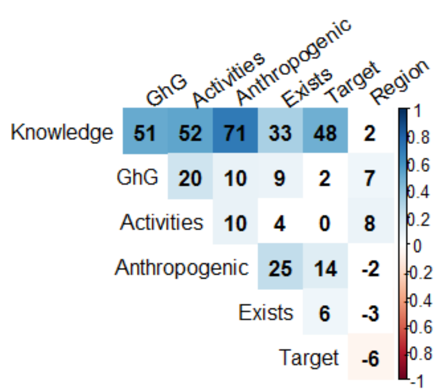


FIGURE H.1 – Correlations between different variables of knowledge on CC.

TABLE H.2 – Robustness of the determinants of Tax & Dividend Acceptance To Knowledge Variables

	Tax & dividend					
	(1)	(2)	(3)	(4)	(5)	(6)
Knowledge on CC	0.029***					
	(0.009)					
CC is Anthropogenic		0.068***				
		(0.019)				
CC Exists			0.115**			
			(0.051)			
Score GhG				0.002		
				(0.009)		
Score Activities					0.005	
					(0.009)	
Score Target proximity						0.015*
						(0.008)
Ecologist	0.126***	0.130***	0.135***	0.135***	0.134***	0.132***
	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)
Yellow Vests : PNR	−0.021	−0.019	−0.023	−0.023	−0.023	−0.024
	(0.032)	(0.032)	(0.032)	(0.032)	(0.032)	(0.032)
Yellow Vests : understands	−0.144***	−0.144***	−0.146***	−0.146***	−0.145***	−0.146***
	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)
Yellow Vests : supports	−0.222***	−0.222***	−0.226***	−0.228***	−0.227***	−0.227***
	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)
Yellow Vests : is part	−0.214***	−0.215***	−0.218***	−0.226***	−0.225***	−0.225***
	(0.043)	(0.043)	(0.043)	(0.042)	(0.043)	(0.042)
Left-right : Extreme-left	−0.040	−0.038	−0.028	−0.033	−0.033	−0.037
	(0.056)	(0.056)	(0.056)	(0.056)	(0.056)	(0.056)
Left-right : Left	0.072***	0.072***	0.075***	0.075***	0.074***	0.075***
	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)	(0.027)
Left-right : Center	0.051*	0.053*	0.052*	0.053*	0.053*	0.054*
	(0.030)	(0.030)	(0.030)	(0.030)	(0.030)	(0.030)
Left-right : Right	−0.022	−0.022	−0.023	−0.023	−0.023	−0.022
	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)
Left-right : Extreme-right	−0.041	−0.044	−0.046	−0.045	−0.044	−0.045
	(0.034)	(0.034)	(0.034)	(0.034)	(0.034)	(0.034)
Sex : Male	−0.053***	−0.047***	−0.046***	−0.048***	−0.049***	−0.048***
	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)
Additional covariates	✓		✓	✓	✓	✓
Observations	3,002	3,002	3,002	3,002	3,002	3,002
R^2	0.150	0.151	0.149	0.147	0.147	0.148

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are the same as in Table II.

I Logit regressions for determinants

TABLE I.1 – Determinants of attitudes towards climate change (CC) with logit regressions.

	CC is anthropogenic			CC is disastrous	
	(1)	(2)	(3)	(4)	(5)
Interest in politics (0 to 2)	0.034***			0.045***	
	(0.013)			(0.014)	
Ecologist	0.144***			0.186***	
	(0.021)			(0.027)	
Yellow Vests : PNR	−0.097***			−0.069**	
	(0.036)			(0.034)	
Yellow Vests : understands	−0.034			−0.040*	
	(0.023)			(0.024)	
Yellow Vests : supports	−0.101***			−0.052**	
	(0.025)			(0.025)	
Yellow Vests : is part	−0.196***			−0.079*	
	(0.047)			(0.044)	
Left-right : Extreme-left	0.121**		0.079	0.070	0.006
	(0.047)		(0.071)	(0.064)	(0.088)
Left-right : Left	0.088***		0.050	0.104***	−0.006
	(0.025)		(0.045)	(0.030)	(0.053)
Left-right : Center	0.011		0.009	0.030	−0.072
	(0.030)		(0.044)	(0.032)	(0.048)
Left-right : Right	−0.031		−0.032	−0.029	−0.138***
	(0.029)		(0.046)	(0.031)	(0.048)
Left-right : Extreme-right	−0.012		−0.025	0.023	−0.081
	(0.034)		(0.056)	(0.038)	(0.062)
Diploma : *CAP* or *BEP*	0.042**		0.039*	−0.022	−0.015
	(0.020)		(0.021)	(0.025)	(0.026)
Diploma : *Baccalauréat*	0.063***		0.111***	0.025	0.121***
	(0.024)		(0.024)	(0.029)	(0.030)
Diploma : Higher	0.093***		0.165***	0.095***	0.234***
	(0.025)		(0.024)	(0.031)	(0.030)
Diploma × Left-right			−0.010		−0.004
			(0.008)		(0.009)
Diploma × Left-right : Indeterminate			0.005		−0.024
			(0.015)		(0.016)
Age : 25 – 34	0.048	−0.040		0.018	
	(0.042)	(0.041)		(0.047)	
Age : 35 – 49	−0.008	−0.113***		0.026	
	(0.043)	(0.035)		(0.045)	
Age : 50 – 64	0.005	−0.116***		−0.036	
	(0.045)	(0.034)		(0.047)	
Age : ≥ 65	−0.095*	−0.228***		−0.087	
	(0.057)	(0.035)		(0.056)	
Income (k€/month)	−0.011			−0.010	
	(0.008)			(0.009)	
Sex : Male	−0.024			0.003	
	(0.018)			(0.019)	
Size of town (1 to 5)	0.006			0.007	
	(0.008)			(0.008)	
Additional covariates	✓			✓	
Observations	3,002	3,002	3,002	3,002	3,002

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Interaction term is computed using numeric variables. Omitted modalities are : *Yellow Vests : opposes*, *Left-right : Indeterminate*, *Diploma : Brevet or no diploma*, *Age : 18 – 24*. Additional covariates are defined in Appendix C.

TABLE I.2 – Determinants of attitudes towards climate policies with logit regressions.

	Tax & dividend		Share of policies	Ecological lifestyle
	(1)	(2)	(3)	(4)
Knowledge on CC	0.029***	0.049***	0.046***	0.092***
	(0.009)	(0.009)	(0.010)	(0.010)
CC is disastrous	0.023	0.035*	0.081***	0.137***
	(0.017)	(0.018)	(0.020)	(0.018)
Interest in politics (0 to 2)	−0.019		0.032**	0.028**
	(0.013)		(0.014)	(0.013)
Ecologist	0.107***		0.077***	0.173***
	(0.025)		(0.028)	(0.023)
Yellow Vests : PNR	−0.022		−0.054	−0.087**
	(0.028)		(0.036)	(0.034)
Yellow Vests : understands	−0.117***		−0.025	−0.009
	(0.018)		(0.024)	(0.022)
Yellow Vests : supports	−0.207***		−0.050*	−0.020
	(0.019)		(0.026)	(0.024)
Yellow Vests : is part	−0.177***		−0.080*	−0.026
	(0.028)		(0.047)	(0.042)
Left-right : Extreme-left	−0.035		0.022	0.083
	(0.055)		(0.065)	(0.055)
Left-right : Left	0.070***		−0.003	0.039
	(0.027)		(0.030)	(0.027)
Left-right : Center	0.051*		0.013	0.096***
	(0.029)		(0.033)	(0.028)
Left-right : Right	−0.022		0.009	0.010
	(0.027)		(0.032)	(0.028)
Left-right : Extreme-right	−0.076**		−0.023	0.010
	(0.034)		(0.039)	(0.033)
Diploma (1 to 4)	−0.002	0.004	0.007	−0.007
	(0.009)	(0.008)	(0.010)	(0.009)
Age : 25 – 34	−0.039	−0.079***	−0.024	0.032
	(0.038)	(0.028)	(0.048)	(0.042)
Age : 35 – 49	−0.041	−0.067**	−0.015	0.051
	(0.037)	(0.026)	(0.046)	(0.040)
Age : 50 – 64	−0.043	−0.078***	−0.002	0.059
	(0.040)	(0.027)	(0.049)	(0.042)
Age : $\geq$ 65	−0.066	−0.074***	0.001	0.016
	(0.046)	(0.028)	(0.058)	(0.051)
Income (k€/month)	0.0002	0.001	0.010	−0.005
	(0.008)	(0.004)	(0.009)	(0.009)
Sex : Male	−0.051***	−0.070***	−0.027	−0.066***
	(0.017)	(0.017)	(0.020)	(0.018)
Size of town (1 to 5)	0.021***	0.035***	0.001	−0.005
	(0.008)	(0.007)	(0.009)	(0.008)
Frequency of public transit	−0.006	0.012*	−0.003	0.023***
	(0.007)	(0.006)	(0.008)	(0.008)
Additional covariates	✓		✓	✓
Observations	3,002	3,002	3,002	3,002

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Average marginal effects are reported, with standard errors in parentheses. Omitted variables are *Yellow Vests : opposes*, *Age : 18 – 24* and *Left-right : Indeterminate*. Additional covariates are defined in Appendix C.

J Robustness for the absence of cultural cognition effect

TABLE J.1 – Robustness of the absence interaction on perceived effects between political orientation and knowledge.

	CC is disastrous		
	(1)	(2)	(3)
Constant	0.404***	0.510***	0.458***
	(0.035)	(0.056)	(0.017)
Yellow Vests : PNR	−0.049		−0.021
	(0.041)		(0.033)
Yellow Vests : understands	−0.013		0.001
	(0.034)		(0.023)
Yellow Vests : supports	−0.020		0.002
	(0.051)		(0.023)
Yellow Vests : is part	−0.049		0.024
	(0.079)		(0.044)
Left-right : Left		−0.004	
		(0.059)	
Left-right : Center		−0.071	
		(0.060)	
Left-right : Right		−0.119**	
		(0.060)	
Left-right : Extreme-right		−0.054	
		(0.063)	
Diploma : *CAP* or *BEP*	−0.029		
	(0.024)		
Diploma : *Baccalauréat*	0.109***		
	(0.027)		
Diploma : Higher	0.203***		
	(0.024)		
Knowledge CC		0.174***	0.188***
		(0.011)	(0.009)
Diploma × Yellow Vests	−0.001		
	(0.009)		
Knowledge CC × Left-right		−0.007	
		(0.009)	
Knowledge CC × Yellow Vests			0.001
			(0.010)
Observations	3,002	1,813	3,002
R^2	0.039	0.138	0.145

*p<0.1 ; **p<0.05 ; ***p<0.01

NOTE : Standard errors are reported in parentheses. Interaction term is computed using numeric variables. Omitted modalities are : *Yellow Vests : opposes*, *Left-right : Extreme-left*, *Diploma : Brevet or no diploma*.

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