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Efficiency improvement and climate change: what energy policies ?

Deici Alejandra Giraldo Hurtado

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L'UNIVERSITÉ DE RENNES 1

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Par

Deici Alejandra GIRALDO HURTADO

**Efficiency improvement and Climate change :
what energy policies ?**

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Already, the environment is trying to tell us that certain stresses are becoming excessive.

— Small is beautiful, E.F. Schumacher (1973)

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Glossary

Common Reporting Framework (CRF) Guidelines from the United Nations Framework Convention on Climate Change (UNFCCC) to estimate and report all anthropogenic emissions and removals of greenhouse gases. The source categories are grouped into the major sectors. For more details, see the Common Reporting Framework.

Consumption units To compare the living standards of households of different size or composition, income is divided by the number of consumption units (CUs). These are generally calculated as follows:

1 CU for the first adult in the household, 0.5 CU for other people aged 14 or over, 0.3 UC for children under 14 years old.

This equivalence scale takes into account economies of scale within the household. Indeed, the needs of a household do not increase in strict proportion to its size. When several people live together, it is not necessary to multiply all consumer goods (especially durable consumer goods) by the number of people to keep the same standard of living (Glossary Insee, 2021).

Road motor vehicle A road vehicle fitted with an engine whence it derives its sole means of propulsion, which is normally used for carrying persons or goods or for drawing, on the road, vehicles used for the carriage of persons or goods (Intersecretariat Working Group on Transport Statistics, 2003).

Passenger road vehicle A road vehicle designed, exclusively or primarily, to carry one or more persons (Intersecretariat Working Group on Transport Statistics, 2003)

Private car or vehicle It is a type of passenger road vehicle used by households.

Horsepower of road vehicle It is the power of the vehicle's engine. It can also be designated by the terms administrative power or fiscal horsepower, abbreviated CV for horsepower (Démarches Carte Grise, 2021).

Vehicle-kilometer Unit of measurement representing the movement of a road motor vehicle over one kilometer (Intersecretariat Working Group on Transport Statistics, 2003).

Fuel consumption Is the amount of fuel used per unit distance; for example, litres per 100 kilometres (L/100 km).

Fuel economy Is the distance made per unit of fuel; for example, Vehicle-kilometer per liter of fuel.

Fuel efficiency The capacity of a vehicle to obtain energy from fuel.

Kilograms of oil equivalent Kilogram(s) of oil equivalent, usually abbreviated as kgoe, is a normalized unit of energy. By convention it is equivalent to the approximate amount of energy that can be extracted from one kilogram of crude oil. It is a standardized unit, assigned a net calorific value of 41 868 kilojoules/kg and may be used to compare the energy from different sources (Glossary Eurostat, 2021).

A liter of petrol is equivalent to 33 572.2 kilojoules. A liter of diesel is equivalent to 38 290.4 kilojoules (U.S. Energy Information Administration).

Odometer readings The numeric value displayed on the vehicle’s odometer readout, which measures the actual distance a vehicle has traveled.

Classification of individual consumption by purpose (COICOP) It is a classification developed by the United Nations Statistics Division to classify and analyze individual consumption expenditures incurred by households, non-profit institutions serving households and general government according to their purpose. It includes categories such as clothing and footwear, housing, water, electricity, and gas and other fuels (Glossary Eurostat, 2021).

Hydrological Cycle It is also known as the “water cycle”; it is the normal water recycling system on Earth. Due to solar radiation, water evaporates, generally from the sea, lakes, etc. and from plant leaves, through the mechanism of transpiration. As the steam rises in the atmosphere, it is being cooled, condensed, and returned to the land and the sea as precipitation. Precipitation falls on the earth as surface water and shapes the surface, creating thus streams of water that result in lakes and rivers. A part of the water precipitating penetrates the ground and moves downward through the incisions, forming aquifers. Finally, a part of the surface and underground water leads to sea (Inglezakis et al., 2016).

Techno-economic orientation (OTEX) The 2003 reform of the common agricultural policy instituting the decoupling of aid linked to production led to the creation of the concept of standard gross production (PBS) which succeeds the old concept of MBS, which is now obsolete. The result is a new European typology of agricultural holdings.

This new classification of farms according to their specialization (OTEX) and their economic size is applied for the first time for the dissemination of the results of the 2010 agricultural census (then to the following structure surveys) as well as to the network of agricultural accounting information.

A farm is specialized in an orientation if the PBS (gross standard production) of the production (s) concerned exceeds two thirds of the total.

OTEX is a European classification (Glossary Insee, 2021).

Acronyms

- **EU:** European Union
- **EC:** European Commission
- **EEA:** European Environmental Agency
- **GHG:** Greenhouse gas
- **IPCC:** Intergovernmental Panel on Climate Change
- **ITDP:** Institute for Transportation & Development Policy
- **FADN:** Farm accountancy data network
- **NTTS:** National Transport and Travel Survey
- **UNFCCC:** United Nations Framework Convention on Climate Change

Résumé en français

Au premier trimestre 2020, le monde a tremblé face à une pandémie dévastatrice. La moitié de la population mondiale était confinée, tandis que les gouvernements tentaient de mettre un terme à la propagation du virus. Après seulement deux semaines de confinement, la qualité de l'air s'est améliorée. Un an après les premières mesures, les émissions de CO₂ ont chuté à un niveau qui pourrait effectivement permettre à l'Union européenne (UE) d'atteindre l'objectif de 20 % d'énergies renouvelables d'ici 2020 (EEA, 2020b). Sans surprise, les émissions de CO₂ sont directement liées à l'activité économique, c'est pourquoi les réductions les plus élevées des émissions de carbone coïncident avec des périodes de crise économique. Néanmoins, une fois l'activité récupérée, la tendance à la hausse reprend (Pindyck, 2020).

L'ampleur de l'influence humaine sur la planète est telle que de nombreux scientifiques considèrent que la Terre vit une transition vers une nouvelle époque géologique, déterminée de manière significative par les choix et l'action humains, appelée l'Anthropocène. Des activités telles que les procédés industriels, la combustion de combustibles fossiles et la déforestation ont conduit à une augmentation moyenne de la température de 1°C au-dessus des niveaux préindustriels. L'augmentation de la concentration mondiale de CO₂ est d'environ 20 ppm (parties par million) par décennie depuis 2000, ce qui est plus rapide que toute augmentation de CO₂ enregistrée au cours des 800 000 dernières années (IPCC, 2018 ; Von Weizsacker, 2009).

Le niveau de réchauffement actuel a déjà impacté les populations, les moyens de subsistance et les écosystèmes naturels partout dans le monde. La planète est confrontée à des

événements météorologiques extrêmes, la perte de biodiversité et l'élévation du niveau de la mer, ce qui entraîne des risques sans précédent, en particulier pour les communautés les plus vulnérables. Le réchauffement climatique atteindra probablement 1,5°C dans les 10 à 30 prochaines années s'il continue d'augmenter au rythme actuel. De plus, dans son dernier rapport, le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC or IPCC en anglais, 2018) prévoit que le réchauffement pourrait dépasser 1,5°C dans les décennies suivantes si les émissions de Gaz à Effet de Serre (GES) ne diminuent pas rapidement d'ici 2030.

Au cours des dernières décennies, d'énormes progrès ont été accomplis. Le rapport entre le PIB et le CO₂, défini comme l'intensité carbone, a considérablement baissé au cours des 50 dernières années dans le monde entier. Les progrès technologiques ont rendu la production moins intensive en énergie et, par conséquent, de plus faibles quantités de carbone sont libérées (Pindyck, 2020). Ce progrès technologique a également été reflété du côté de la consommation, en augmentant l'efficacité des appareils consommateurs d'énergie utilisés par les ménages partout dans le monde. En fait, les politiques d'amélioration de l'efficacité ont guidé une grande partie de l'action et des progrès en matière de changement climatique.

L'augmentation de l'efficacité d'un système est souvent considérée comme un moyen de réduire l'utilisation intensive des ressources naturelles. Cette stratégie constitue un pilier important de l'atténuation et de l'adaptation au changement climatique. Selon l'Agence européenne pour l'environnement (AEE), les politiques d'atténuation visent à réduire les émissions de carbone liées aux activités humaines. Ces politiques visent principalement la production et la consommation d'énergie, par exemple le développement des énergies vertes du côté de la production ou le développement de véhicules et de bâtiments résidentiels plus efficaces (moins consommateurs d'énergie) du côté de la consommation.

Les politiques d'adaptation au climat sont conçues pour aider les sociétés, les secteurs économiques ou les écosystèmes à mieux faire face aux conséquences du changement climatique. Les impacts du changement climatique ont déjà commencé à se manifester, sous

la forme d'événements météorologiques violents, tels que la sécheresse et les inondations, qui deviennent plus fréquents à mesure que les températures augmentent. Sur ce front, l'amélioration de l'efficacité est au centre des politiques de conservation de l'eau, principalement dans le secteur agricole.

Si les progrès sont indéniables, la rapidité de ces réalisations est toujours en retard par rapport à la progression du réchauffement climatique. Limiter le réchauffement à 1,5°C , tel que visé par l'Accord de Paris sur le changement climatique de 2015, exigera une échelle et un rythme de changement plus importants pour transformer les systèmes énergétiques, terrestres, urbains et industriels à l'échelle mondiale (IPCC, 2018).

Paradoxalement, les politiques d'efficacité, qui ont stimulé certaines des avancées liées au climat, peuvent avoir contribué à la lenteur générale des progrès. Les améliorations techniques n'impliquent pas nécessairement des économies de ressources. La littérature économique a observé des ajustements dans le comportement des producteurs et des consommateurs après de telles améliorations, ce qui se traduit souvent par une demande accrue de la ressource, un effet opposé à celui visé par la politique. L'augmentation de la demande suite à une amélioration de l'efficacité technique d'un dispositif de conversion de ressources, est connue sous le nom d'effet rebond (Font Vivanco et al., 2018).

Le cas le plus documenté d'effet rebond est celui de l'utilisation d'un véhicule privé. Les gouvernements du monde entier ont mis en œuvre des politiques visant à réduire la consommation de carburant en augmentant le rendement énergétique des véhicules à moteur. Lorsqu'un véhicule bénéficie d'une amélioration de l'efficacité, les individus peuvent parcourir la même distance avec moins de carburant. Cela signifie que le prix réel de la conduite diminue et qu'ils disposent alors d'un revenu supplémentaire. Ce nouveau revenu est généralement dépensé pour conduire davantage. Les gains finaux en carburant sont donc plus faibles en raison du rebond de la demande de conduite (Sorrell, 2012).

Un autre cas bien documenté de l'effet rebond concerne les immeubles résidentiels. Les données empiriques montrent que les gains calculés par la politique et ceux effectivement observés diffèrent considérablement. L'amélioration de l'efficacité modifie le coût perçu

du confort et peut ainsi générer des changements dans les modes de consommation. En tant que tel, l'effet rebond est déterminé par des caractéristiques du ménage telles que le revenu (Aydin et al., 2017).

Du côté de la production, un résultat similaire est observé. La littérature récente a montré l'existence d'effets de rebond de l'eau d'irrigation en agriculture. Une fois de plus, les agriculteurs adapteraient leurs comportements de production, ce qui pourrait entraîner une demande en eau plus élevée. Cependant, étant du côté de la production, l'effet rebond sur l'eau d'irrigation diffère sur certains points de ceux décrits précédemment. Outre l'eau, d'autres ressources sont nécessaires pour la production agricole, à savoir l'énergie et la terre (Sears et al., 2018). Cela crée une relation entre ces ressources et, en particulier, indique un point de rencontre entre les politiques environnementales d'atténuation et d'adaptation.

Au final, les politiques de changement climatique, telles que l'amélioration de l'efficacité, peuvent être réduites à un problème de gestion des ressources. Cependant, les individus réagissent à ces politiques en adaptant leur comportement, ce qui conduit à des résultats inattendus.

Cette thèse vise à éclairer l'effet rebond lié à l'utilisation de l'énergie (carburant et résidentiel) et de l'eau d'irrigation. Ces travaux s'appuient sur des méthodes théoriques et empiriques pour fournir trois analyses sur les politiques d'amélioration de l'efficacité en France. En outre, cette thèse dresse une analyse des politiques dans l'interdépendance des efforts d'atténuation et d'adaptation et comment ils s'intègrent dans le panorama global de l'action contre le changement climatique.

Le rappel de cette introduction motive les principales questions de recherche abordées dans cette thèse. La première section présente des chiffres récents sur le changement climatique et les émissions de GES dans l'UE, principalement axés sur les secteurs des transports, du résidentiel et de l'agriculture. La deuxième section résume les politiques environnementales qui reposent sur l'amélioration de l'efficacité dans l'UE. La troisième section définit l'effet rebond et présente quelques résultats clés de la littérature récente.

La section suivante décrit la structure de cette thèse organisée en trois chapitres et la section finale présente la conclusion.

Principaux vecteurs du réchauffement climatique

Cette section se concentre sur la discussion des contributions aux émissions de GES des trois secteurs qui émettent le plus de GES (après l’approvisionnement énergétique et les secteurs industriels) : les transports, le résidentiel et l’agriculture.

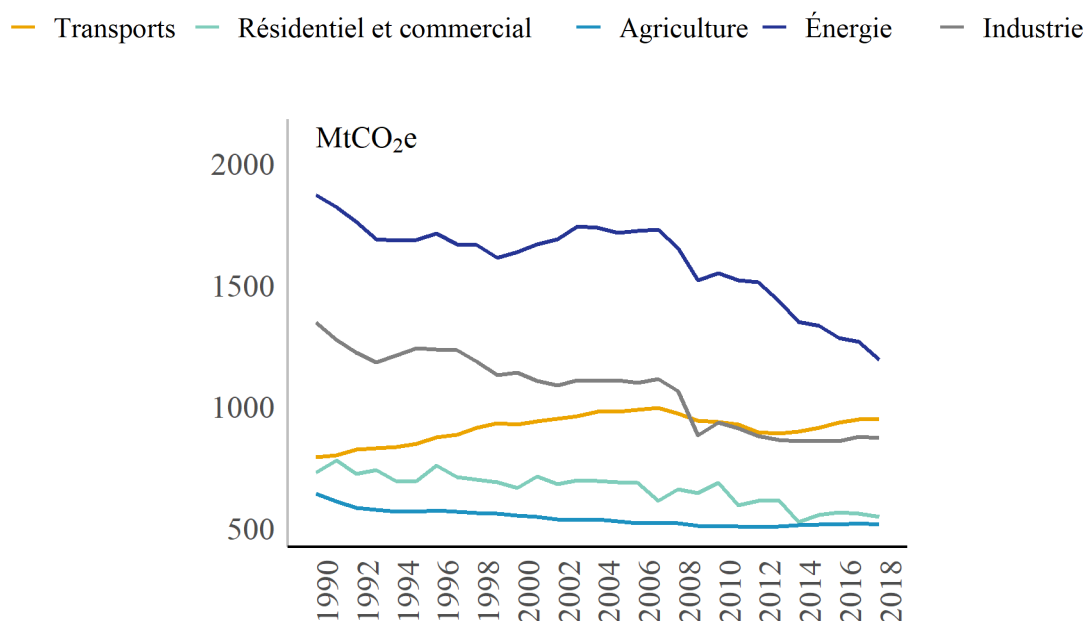
La Figure 1 présente l’évolution de toutes les émissions de GES (en millions de tonnes équivalent CO₂) dans l’UE et au Royaume-Uni entre 1990 et 2018 pour les cinq secteurs les plus émetteurs¹.

Les principaux points à retenir de cette figure sont au nombre de trois. Tout d’abord, les émissions (en particulier le CO₂) ont régulièrement diminué depuis le début des années 90. Ensuite, tous les secteurs ont contribué positivement à cette tendance, à l’exception du transport. Pendant cette période, le transport intérieur a affiché une tendance à la hausse jusqu’en 2008, date à laquelle il a dépassé les émissions industrielles. Enfin, les secteurs résidentiel et agricole affichent une tendance à la baisse moins prononcée. Cette tendance suggère que le potentiel d’économies est le plus grand dans ces trois secteurs.

Dans le secteur des transports, les émissions n’ont cessé d’augmenter depuis 1990, sauf pendant une courte période lors de la crise économique de 2008-2009. Cette tendance est observée en dépit du fait que de nombreuses politiques climatiques sont orientées vers les transports de passagers et de marchandises, notamment le déploiement de véhicules moins intensifs en carbone et plus efficaces sur le marché. La tendance récente peut s’expliquer par les modes de consommation des voitures particulières. Ce type de véhicules représente plus de la moitié des émissions de ce secteur. L’une des raisons peut être que dans l’UE, en moyenne, des voitures plus puissantes sont vendues et que le niveau des émissions de CO₂ par km parmi ces nouveaux véhicules est plus élevé (EEA, 2020a).

¹Les émissions comptabilisées selon le cadre de déclaration commun de la Convention-cadre des Nations unies sur le changement climatique (CCNUCC).

FIGURE 1 : Émissions de gaz à effet de serre par secteurs dans l'UE-27 et le Royaume-Uni



Source : EEA (2020a).

Note de lecture : Chaque courbe représente l'évolution des émissions de GES pour la période 1990-2018 par secteur en millions de tonnes équivalent CO₂. Les agrégations sectorielles correspondent à celles du cadre de déclaration commun de la Convention-cadre des Nations unies sur le changement climatique (CCNUCC).

On observera, probablement, une baisse des émissions pour 2020-2021 en raison du ralentissement de l'activité économique pendant la pandémie. Cependant, cet effet peut ne pas être durable et nous pourrions même voir une augmentation des émissions provenant du transport personnel. Selon l'Institut pour le Politiques en Transports et Développement (ITDP, 2021), après un premier ralentissement de l'utilisation des véhicules privés, le trafic repart à la hausse partout dans le monde, atteignant, dans certains cas, des niveaux plus élevés que ceux observés avant la pandémie. Face à d'éventuelles infections, les individus se sont retrouvés à privilégier l'utilisation de véhicules privés. Dans certains pays riches, les achats de véhicules ont, en effet, augmenté.

Dans le secteur résidentiel, l'amélioration des normes d'isolation dans les bâtiments et une consommation d'énergie moins intensive en carbone ont conduit à une diminution de la demande de chauffage des locaux dans l'UE depuis 1990. En 2016, le secteur résidentiel

correspond à un quart de la consommation d'énergie finale ² dans l'UE et la demande devrait augmenter d'ici 2040.

À ce titre, la tendance observée dans ces deux secteurs représente un défi pour la réalisation des objectifs 2030 (EEA, 2020a).

Le secteur agricole diffère des deux autres car sa relation avec le réchauffement climatique est plus complexe. Premièrement, ce secteur est soumis à des politiques d'atténuation du changement climatique car la consommation d'énergie dans l'agriculture représente plus de 12 % des émissions dans l'UE (Figure 1).

Deuxièmement, il nécessite des politiques d'adaptation au climat, car l'eau est un input essentiel dans l'agriculture et les épisodes de stress hydrique sont plus fréquents avec le réchauffement climatique. L'utilisation agricole de l'eau pour l'irrigation représente 70 % de la consommation d'eau dans le monde et 59 % dans l'UE en 2017. Ainsi, ce secteur exerce le plus de pression sur les ressources renouvelables en eau douce. Ce problème devient plus urgent à mesure que la population continue d'augmenter et que le changement climatique s'accélère. Par conséquent, ce secteur a fait l'objet d'un ensemble différent de politiques environnementales, principalement en faveur des économies de l'eau.

Quelles politiques pour lutter contre le changement climatique ?

Les politiques d'amélioration de l'efficacité sont au cœur de l'action climatique, en tant que stratégie d'atténuation et d'adaptation au changement climatique. En effet, l'augmentation de l'efficacité des systèmes est considérée comme un moyen de réduire l'utilisation intensive des ressources naturelles.

En ce qui concerne l'atténuation, en 2007, l'UE a fixé les trois objectifs clés pour 2020 : 20 % de réduction des GES par rapport aux niveaux de 1990, 20 % d'énergie de l'UE

²Utilisation d'énergie des ménages pour le chauffage des locaux et de l'eau, la climatisation, la cuisson, l'éclairage et les appareils électriques et autres utilisations finales, à l'exclusion des transports.

provenant d'énergies renouvelables et 20 % d'amélioration de l'efficacité énergétique. Cela faisait partie de la stratégie visant à parvenir à une réduction nette de 55% des émissions de GES d'ici 2030 et à une UE climatiquement neutre d'ici 2050.

L'amélioration de l'efficacité énergétique a été un facteur déterminant dans la réalisation des objectifs de 2020, principalement à travers la diminution des émissions de carbone provenant de l'utilisation des véhicules et des bâtiments résidentiels, les secteurs où le potentiel d'économies est le plus important (IEA, 2020).

En 2009, l'UE a introduit les premières normes d'émissions obligatoires de CO₂ pour les voitures particulières et les véhicules utilitaires légers. Elle a fixé un objectif pour 2015 de 130 gCO₂/km pour la moyenne du parc de tous les constructeurs confondus. Cette politique a eu des résultats notables. Le niveau moyen d'émission de CO₂ des voitures neuves est passé d'environ 160 gCO₂/km en 2006 à 132 gCO₂/km en 2012 (ICCT, 2014). En 2012, le nouvel objectif pour les voitures particulières en 2020 a été fixé à 95 gCO₂/km.

Du côté de l'adaptation, des mesures d'efficacité ont été appliquées à l'eau d'irrigation pour éviter l'épuisement de la ressource. La feuille de route de l'UE pour une Europe efficace dans l'utilisation des ressources (2011) incluait un objectif pour 2020 : l'extraction d'eau devrait rester en dessous de 20 % des ressources renouvelables en eau douce disponibles.

L'extraction et l'utilisation de l'eau en Europe ont diminué de 17 % entre 2000 et 2017, tandis que la valeur ajoutée brute totale générée par tous les secteurs économiques a augmenté de 59 %. Cela suggère une tendance au découplage au cours de cette période, bien que les résultats régionaux et nationaux spécifiques puissent différer considérablement. Cette tendance positive est le résultat des améliorations technologiques dans l'efficacité d'utilisation de l'eau des appareils, des politiques de tarification de l'eau et de la transition socio-économique en Europe de l'Est (AEE, 2019).

Certaines estimations préliminaires suggèrent que l'efficacité de l'irrigation en Europe se situe entre 50 % et 70 %. Cela signifie qu'entre un tiers et la moitié de l'eau utilisée pour l'irrigation est perdue pendant le transport vers la parcelle, en raison de l'évaporation ou du ruissellement. Cela implique qu'il y a encore place à l'amélioration de l'efficacité de

l'irrigation (AEE, 2019). Les programmes de subventions sont mis en œuvre par les gouvernements afin de promouvoir ce que l'on appelle l'utilisation de technologies d'irrigation plus efficaces (EC, 2011).

Selon le dernier rapport GIEC (2018), les programmes nationaux d'atténuation et d'adaptation ne sont pas suffisants pour limiter le réchauffement à 1,5 °C comme envisagé dans l'Accord de Paris de 2015. Le rythme du changement n'est pas aussi rapide que l'augmentation de la température.

Une partie de ce retard peut s'expliquer par l'examen des politiques d'efficacité. La littérature économique a observé l'existence de l'effet rebond, un résultat indésirable résultant d'ajustements de comportement individuels suite à une amélioration de l'efficacité.

Lorsqu'un système énergétique devient plus efficace, le coût réel du service énergétique unitaire peut baisser. Dans un tel cas, les gens seraient incités à consommer plus de services énergétiques, augmentant ainsi la demande d'énergie. Cette augmentation de la demande d'énergie, ou effet rebond, déterminera l'efficacité réelle de ces politiques pour réduire la consommation d'énergie et les émissions GES associées (Sorrell et al., 2009). Cela peut donner un aperçu des raisons pour lesquelles les émissions de GES dans les transports continuent d'augmenter alors que les véhicules deviennent de plus en plus éconergétiques.

L'UE n'a pas atteint l'objectif 2020 de 95 gCO₂/km. En 2019, les émissions moyennes des voitures neuves étaient de 122,4 gCO₂/km. En moyenne, des voitures plus puissantes sont vendues, d'où le niveau plus élevé d'émissions de CO₂ par km parmi ces nouveaux véhicules. En outre, la consommation d'énergie a amorcé une tendance à la hausse dans les transports et les bâtiments après 2014, période de reprise économique après la crise financière (EEA, 2020a).

De même, les améliorations des technologies d'irrigation peuvent conduire les agriculteurs à augmenter leur demande en eau. La littérature récente a souligné que l'introduction de systèmes d'irrigation plus efficaces peut, en définitive, augmenter l'épuisement des ressources en eau. Dans ce cas, il y a d'autres éléments en jeu. L'amélioration d'un système d'irrigation abaisse le coût unitaire réel du service d'eau, mais peut également améliorer

la productivité des cultures et augmenter les charges en énergie.

La section suivante propose une définition formelle de l'effet rebond, expose la principale différence entre les effets de rebond de l'énergie et de l'eau et présente quelques résultats clés de la littérature récente.

Effet rebond induit par les améliorations d'efficacité

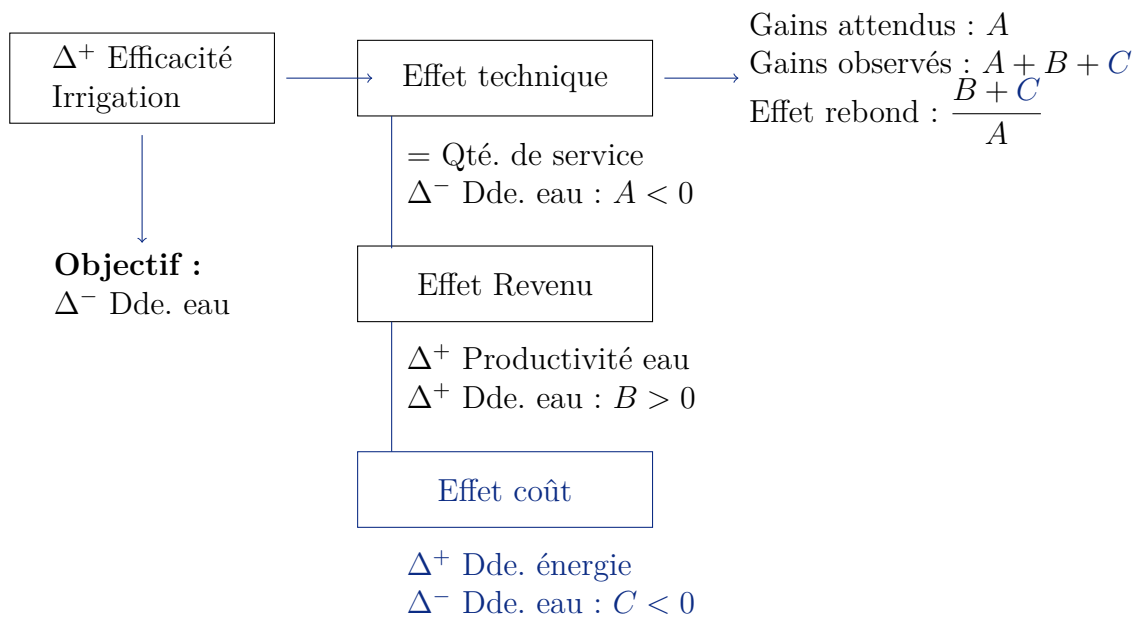
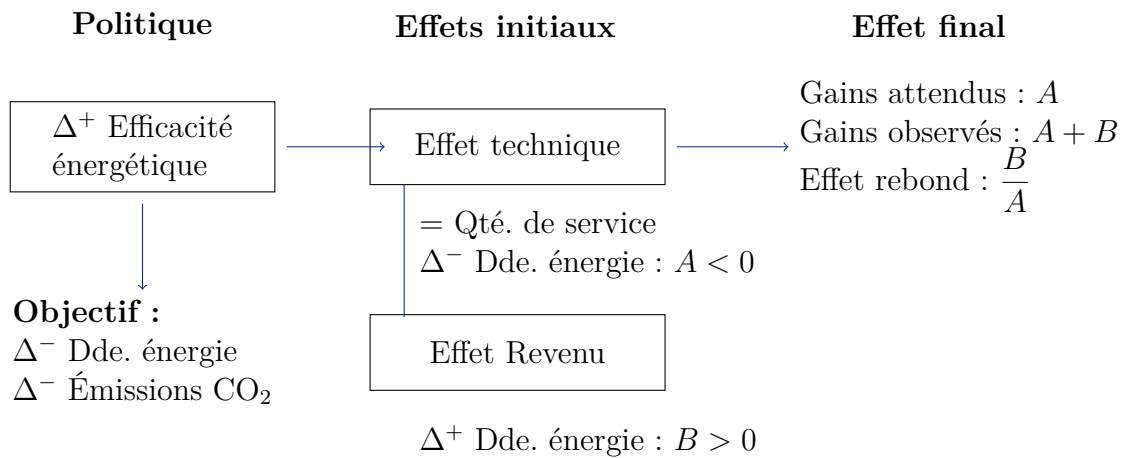
L'effet rebond est également connu sous le nom de Paradoxe de Jevons, du nom de William Stanley Jevons. Il a été le premier à observer les conséquences inattendues des améliorations d'efficacité en 1865 avec la machine à vapeur Watt. Jevons a montré que l'amélioration de l'efficacité des machines à vapeur alimentées au charbon a conduit à une augmentation de l'utilisation de la machine à vapeur dans toutes les industries et donc à une augmentation de la demande de charbon. Il a pensé que c'était un paradoxe, puisque l'amélioration de l'efficacité a été développée pour réduire la consommation de charbon et, à la place, le contraire s'est produit (Sears et al., 2018).

La Figure 2 illustre les mécanismes à l'origine de l'effet rebond. La première colonne présente le type de politique et son objectif. Deux types d'objectifs politiques sont distingués : a) la réduction des émissions de CO₂ liés à la consommation d'énergie et b) la réduction dans l'utilisation de l'eau liée à l'irrigation en agriculture. La deuxième colonne montre les effets initiaux, attendus et inattendus, de la politique. La troisième colonne montre l'effet final de la politique.

L'effet rebond peut être compris comme la conséquence d'une relation de renforcement entre l'efficacité des ressources et l'utilisation des ressources. Après une amélioration de l'efficacité du processus de transformation et d'utilisation des ressources, les individus peuvent ajuster leur réponse aux changements de prix, ce qui entraîne une demande plus élevée pour la ressource (Font Vivanco et al., 2018).

Les améliorations de l'efficacité énergétique permettent à la demande de diminuer, car la même quantité de services peut être obtenue avec moins d'intrants. Cela correspond à

FIGURE 2 : Mécanisme de l'effet rebond dans la consommation d'énergie et d'eau



Note de lecture : Les améliorations de l'efficacité énergétique permettent à la demande de diminuer, car le même nombre de services peut être obtenu avec moins d'intrants (effet technique $A < 0$). Cependant, cela entraîne une diminution du prix réel du service (effet revenu $B > 0$), ce qui fait augmenter la demande. Les gains finaux de la politique sont réduits par le rebond de la demande. De même, lorsqu'une technologie d'irrigation est améliorée, on observe les effets techniques et de revenu (productivité). De plus, il existe un effet de coût ($C < 0$) associé à l'utilisation de l'énergie pour l'irrigation. Cet effet induit une diminution de la demande. Les gains finaux en eau peuvent être supérieurs ou inférieurs aux prévisions, selon l'ampleur des effets sur la productivité et les coûts.

l'effet technique. Les gains de ressources attendus après une amélioration de l'efficacité sont égaux au pourcentage de l'amélioration, dans ce cas représenté par A .

Cependant, l'amélioration de l'efficacité entraîne une diminution du prix réel du service,

généralant un revenu supplémentaire, ou effet revenu, de B , ce qui fait augmenter la demande. En d'autres termes, les individus utilisent leur revenu supplémentaire pour augmenter la consommation de tous les biens et services, y compris les services qui bénéficient de l'amélioration initiale de l'efficacité. Par conséquent, les gains finaux de la politique sont réduits de B . L'effet rebond est quantifié comme l'écart en pourcentage par rapport aux gains attendus initiaux (ratio B/A) (Sorrell, 2012).

Prenons par exemple le cas des objectifs d'efficacité fixés par l'UE. En 2012, l'UE a fixé l'objectif 2020 pour les voitures particulières à 95 gCO₂/km. Cela équivaut à une réduction de plus d'un quart de gCO₂/km ou à une amélioration de l'efficacité de la même proportion. La Commission européenne a estimé que par rapport à 2015, la consommation de carburant diminuera à peu près du même pourcentage, ce qui signifie que $A = -25\%$. Cela permettrait d'économiser 160 millions de tonnes de pétrole entre 2020 et 2030, soit 420 millions de tonnes de CO₂ de moins au cours de la même période.

L'amélioration de l'efficacité réduira le prix réel de la conduite, car la même distance peut être parcourue en utilisant moins de carburant. Supposons que la demande de carburant augmente de $B = 4\%$ entre 2020 et 2030, les gains d'efficacité énergétique (mesurés en termes de consommation de carburant) seraient de 21 % au lieu des 25 % attendus et l'effet rebond sera $4\%/25\% = 16\%$.

Un mécanisme similaire est en jeu lors de l'amélioration des systèmes d'irrigation dans l'agriculture. L'amélioration de l'efficacité diminue les besoins en eau, ce qui diminue les charges d'eau : la même zone peut être irriguée avec moins d'eau (effet technique A). En outre, une eau appliquée plus efficacement augmente la productivité et le rendement des cultures, ce qui peut induire des changements dans le comportement individuel des agriculteurs (effet revenu ou productivité B). Ils peuvent être incités à utiliser plus d'eau soit en irriguant de nouvelles zones agricoles, soit en cultivant des cultures plus gourmandes en eau (Li et Zhao, 2018).

De plus, comme le fonctionnement de tout système d'irrigation nécessite l'utilisation d'énergie, l'effet rebond de l'irrigation a un impact supplémentaire. Un système d'irri-

gation constitue un facteur de production énergivore en agriculture. Des systèmes d'irrigation plus efficaces sont généralement liés à une utilisation plus intensive de l'énergie. Par conséquent, outre l'effet technique et de productivité décrit ci-dessus, une amélioration de la technologie d'irrigation créera un effet de coût (C), associé à l'utilisation de l'énergie, qui aura un impact négatif sur la demande en eau (Gómez et Pérez-Blanco, 2015).

L'impact final des politiques de conservation de l'eau doit tenir compte de ces trois effets. Il peut être supérieur ou inférieur aux prévisions, selon l'ampleur des effets sur la productivité et les coûts. Cependant, chaque fois que la nouvelle technologie est plus énergivore, il y aura toujours un rebond associé à l'utilisation de l'énergie. En d'autres termes, il y a un rebond inter-ressources. Cela implique que l'utilisation de l'eau et de l'énergie dans l'agriculture sont étroitement liées.

Ainsi, prenez un service s qui nécessite une ressource donnée (c'est-à-dire de l'eau ou de l'énergie) pour être produit. La littérature distingue trois types d'effets de rebond résultant de la baisse du prix du service s après une amélioration de l'efficacité. Un *effet rebond direct* se produit lorsque la consommation du service s augmente. Un *effet rebond indirect* se produit lorsque la variation de prix entraîne des changements dans la demande d'autres biens et services intensifs dans la même ressource. Ceci est principalement observé avec les améliorations de l'efficacité énergétique. Enfin, un *effet rebond à l'échelle de l'économie* se produit lorsque la baisse du prix du service s est suivie par des variations des prix des biens intermédiaires et finaux et des ajustements de quantité dans toute l'économie (Sorrell et Dimitropoulos, 2008).

L'effet rebond direct est estimé comme l'élasticité d'efficacité du service s . L'effet rebond indirect est estimé comme l'élasticité des biens et des services autres que s aux variations de l'efficacité de s . Enfin, l'effet rebond à l'échelle de l'économie correspond à la somme des effets direct et indirect (Sorrell, 2012).

Le reste de cette section présente les principaux résultats tirés de la littérature sur l'effet rebond de la demande de carburant, de la demande d'énergie résidentielle et de la demande en eau.

Différentes stratégies empiriques d'estimation

Certaines études estiment le rebond sur la base de modèles à service énergétique unique. Cette méthodologie est largement utilisée dans l'estimation de l'effet rebond direct dans le transport routier, service énergétique pour lequel on trouve le plus d'estimations de cet effet (Sorrell et al., 2009). Ces études se concentrent exclusivement sur les effets de rebond directs et négligent les effets de rebond indirects.

Pour les véhicules, l'effet rebond est généralement quantifié comme le changement en pourcentage des kilomètres parcourus à cause d'une augmentation de 1 % de la consommation de carburant. En d'autres termes, l'élasticité d'efficacité de la distance parcourue. Cependant, en raison de la faible disponibilité des données, la littérature s'appuie principalement sur des définitions alternatives telles que l'élasticité-prix du carburant de la demande de conduite ou la propre élasticité-prix du carburant (Sorrell et Dimitropoulos, 2008). L'approximation de l'effet rebond par l'élasticité-prix des matières premières peut introduire un biais dans la mesure, notamment en présence de substituts. En effet, un changement d'efficacité n'affecte qu'un service particulier, alors qu'une variation de prix affectera tous les services connexes. Néanmoins, le manque de données fait de cette méthode l'une des meilleures approximations de la taille de l'effet rebond (Freire-González, 2017).

L'existence de l'effet rebond dans l'utilisation du véhicule privé est largement acceptée. La magnitude de l'estimation varie considérablement selon le type de données ou la méthodologie. La plupart des études basées sur les données des États-Unis montrent que l'effet rebond dans l'usage de la voiture particulière est faible, allant de 5 à 25 % (Greene, 1992 ; Greene et al., 1999 ; Small et Van Dender, 2007). Cependant, Linn (2016) trouve un effet rebond qui érode environ un tiers des économies de carburant.

Dans les pays européens, il y a moins de travaux et les estimations sont moins concluantes. Les estimations de rebond sont relativement plus élevées que celles des États-Unis, allant de 9 % à 80 % (Frondel et Vance, 2013a ; Stapleton et al., 2016 ; Weber et Farsi, 2014). Les estimations faites dans les économies en développement, comme la Chine, ont tendance

à montrer des effets de rebond plus importants et même parfois supérieur à 100 %. Cela signifie que l'amélioration de l'efficacité du service de trafic peut difficilement réaliser des économies d'énergie (Lin et Liu, 2013 ; Wang et al., 2012 ; Zhang et al., 2017).

D'autres études intègrent de multiples services dans la modélisation de l'effet rebond, notamment en estimant un modèle de demande des ménages. Cette méthodologie a l'avantage de permettre l'estimation des effets de rebond directs et indirects, en estimant les élasticités prix propres et croisées pour un service énergétique donné.

Effet rebond et hétérogénéité des ménages

Même s'il n'y a pas de consensus sur la magnitude de l'effet rebond, les chercheurs s'accordent sur le fait que l'hétérogénéité des ménages joue un rôle important dans l'ampleur de cet effet. En effet, la consommation d'énergie des ménages est étroitement liée à des facteurs socio-économiques tels que le niveau de revenu, les habitudes de dépenses, l'âge ou la zone géographique. Ces caractéristiques déterminent la possibilité pour les ménages de passer à des technologies plus efficaces. En outre, le mode de vie et les besoins particuliers (par exemple les besoins des enfants et des membres âgés de la famille) peuvent également affecter la consommation d'énergie. Par conséquent, comme différents profils de ménages ont des capacités différentes pour adapter leurs choix de consommation, un modèle qui ne tient pas compte de ces hétérogénéités préciserait mal les effets et, vraisemblablement, produirait des résultats avec une validité limitée.

Des résultats récents estiment que 40 % de la consommation d'énergie dans le secteur résidentiel est déterminée par des facteurs techniques et environ 33 % est déterminée par des caractéristiques socio-économiques telles que le revenu, l'âge du ménage et le statut d'occupation (Bakaloglou et Charlier, 2019). Par conséquent, l'analyse de l'effet des préférences individuelles sur la demande d'énergie peut éclairer l'importance de l'hétérogénéité des ménages et de la variabilité de la consommation d'énergie. Cela est particulièrement pertinent, compte tenu de l'ampleur de la demande d'énergie des ménages.

Un élément clé qui manque dans la modélisation du rebond hétérogène est l'existence

de préférences différentes au sein d'un même ménage. Ceci s'explique principalement par le fait que la littérature sur le rebond est basée sur les modèles unitaires traditionnels. Cette approche suppose un ensemble commun de préférences fixes parmi les membres du ménage et maximise une seule fonction d'utilité limitée par la contrainte budgétaire du ménage (d'où le nom unitaire). Dans ce cadre, les ménages agissent comme une seule unité de décision, quel que soit le nombre de membres du ménage. Seul le revenu exogène total explique le comportement des ménages. De plus, ce cadre ne peut pas prendre en compte l'élément public dans la consommation de services énergétiques (comme le chauffage) au sein du ménage (Donni, 2008 ; Vermeulen, 2002).

Prenons par exemple le cas d'un ménage de deux personnes, dans lequel un membre améliore l'un de ses appareils énergétiques et il peut accéder à la même quantité de service énergétique s en utilisant moins d'énergie, ce qui le rend moins cher. Dans la théorie de l'effet rebond, nous avons des effets de substitution et de revenu. À condition que les services aient des substituts proches dans le ménage, cette personne peut les remplacer par la nouvelle technologie. Dans ce cas, nous aurions un effet rebond direct, car la demande de service s augmente en raison d'une amélioration de l'efficacité. De plus, en raison de l'effet revenu, cet individu peut également augmenter la demande d'autres biens et services, intensifs en énergie ou non.

Dans le cadre collectif, le programme du ménage est soumis à un revenu familial unique, mais il prend en compte la répartition de ce revenu entre les membres du ménage et, par conséquent, le poids des préférences de chaque personne dans le processus de prise de décision. En d'autres termes, l'effet revenu peut modifier la répartition du pouvoir entre les membres du ménage, soit en équilibrant, soit en surcompensant leur influence. Les mécanismes derrière l'effet rebond ne sont pas si simples que dans le modèle des ménages unitaires. Le processus de négociation au sein du ménage peut modifier considérablement la taille et la direction (positive ou négative) du rebond.

Jusqu'à présent, seules quelques études ont tenté d'expliquer la demande des ménages pour (certains) services énergétiques en considérant l'existence d'hétérogénéité au sein du

ménage et aucune de ces études ne s'est concentrée sur l'effet rebond. Bargain et Donni (2012), Browning et al. (2013) et Vermeulen et Watteyne (2006) utilisent la théorie des ménages collectifs et les modèles de demande des ménages pour expliquer la demande de biens publics au sein du ménage. Ils considèrent au moins un service énergétique (transports) dans leur modèle. Ils constatent une différence significative entre l'élasticité de la dépense énergétique pour différentes compositions de ménage, à savoir entre un ménage à deux membres et un ménage d'une seule personne dirigé par une femme.

Effets rebond de l'eau et demande d'énergie

Investir dans une technologie d'irrigation économe en eau devrait permettre aux agriculteurs de conserver des rendements similaires en utilisant moins d'eau (Pfeiffer et Lin, 2014a). Cependant, la littérature récente suggère que les programmes d'investissement ne réduisent pas systématiquement la demande d'eau (Lin Lawell, 2016 ; Song et al., 2018). L'amélioration de l'efficacité peut induire des changements dans le comportement individuel des agriculteurs. Ils peuvent être incités à utiliser plus d'eau soit en irriguant une aire plus grande, soit en cultivant des cultures plus gourmandes en eau (Li et Zhao, 2018).

Quelques études analysent les changements des politiques de tarification de l'eau dans différents pays tels que la Chine (Song et al., 2018), l'Espagne (Berbel et al., 2015) et les États-Unis (Li et Zhao, 2018). Ils révèlent que les politiques d'économie d'eau visant à améliorer la productivité de l'eau ne sont pas aussi efficaces que prévu en raison des effets de rebond, allant de 64 % à plus de 100 %, principalement dûs à une augmentation des terres irriguées.

En revanche, certaines études ne trouvent pas d'effet rebond dans l'eau d'irrigation (Peterson et Ding, 2005). D'autres montrent que l'existence de l'effet rebond dépend de la mise en œuvre de réglementations restrictives sur l'utilisation de l'eau et des terres cultivées (Berbel et Mateos, 2014 ; Berbel et al., 2015). L'ambiguïté de ces résultats peut s'expliquer par l'interaction des effets expliqués dans la section précédente.

La littérature montre que les ajustements d'utilisation de l'eau peuvent être observés non

seulement suite à une amélioration de la technologie d'irrigation, mais également suite à une évolution du coût de l'irrigation, notamment en raison d'une consommation d'énergie plus élevée. Étant donné que des systèmes d'irrigation plus efficaces sont directement associés à une demande d'énergie plus élevée, toute variation du niveau d'efficacité d'irrigation aura un effet à la fois sur la demande en eau et sur la demande d'énergie (Belaud et al., 2020).

La part de l'énergie dans les coûts des agriculteurs peut aller de 40 % à 65 %. Dans certains cas, l'importance de l'énergie dans le coût de l'irrigation conduit les agriculteurs à réduire leur consommation d'eau même en dessous des niveaux d'eau requis par la culture, ce qui met en danger les rendements agricoles (Rodríguez-Díaz et al., 2011). Espinosa-Tasón et al. (2020) estiment qu'en Espagne au cours de la période 2005-2013, l'efficacité de l'irrigation augmente de 0,4 % et la consommation d'énergie par m³ augmente de 2,2 %.

La demande en eau peut diminuer en raison des coûts énergétiques plus élevés qui font grimper le coût total de l'extraction de l'eau, et ce au détriment des émissions de gaz à effet de serre plus élevées provenant de l'augmentation de la demande d'énergie. Par conséquent, la question énergétique ne peut être exclue du débat sur l'irrigation efficace en agriculture, car ce résultat implique l'existence d'un effet rebond indirect se produisant comme un effet rebond inter-ressources.

Aperçu de la thèse

Cette thèse vise à contribuer théoriquement et empiriquement aux travaux de recherche sur la méthode d'identification et de mesure de l'effet rebond. Elle est structurée en trois chapitres combinant à la fois des méthodes théoriques et empiriques pour aborder différents aspects de l'effet rebond de la consommation d'énergie et d'eau. En outre, cette thèse englobe un élément de politique publique, qui vise à fournir des éléments supplémentaires à la discussion et à la conception des politiques de changement climatique, en particulier des politiques d'amélioration de l'efficacité.

Les deux premiers chapitres de cette thèse analysent les politiques d'atténuation du chan-

gement climatique basées sur l'amélioration de l'efficacité énergétique, qui visent à réduire la consommation d'énergie dans les ménages. Le premier chapitre présente une analyse empirique qui compare les différentes méthodes utilisées pour estimer l'effet rebond de l'utilisation du véhicule privé. Le deuxième chapitre propose un nouveau cadre théorique d'analyse de l'effet rebond, fondé sur l'hétérogénéité des ménages, qui peut être utilisé pour estimer l'effet rebond résidentiel et de la voiture personnelle. Le dernier chapitre ajoute une nouvelle dimension à la discussion en intégrant l'analyse des politiques d'adaptation au climat dans l'agriculture. Ce chapitre évalue l'effet rebond dans l'utilisation de l'eau d'irrigation et examine les implications de la relation existante entre les politiques d'atténuation du changement climatique et d'adaptation.

Chapitre 1. Demande de conduite et économies de carburant : le cas Français

Dans ce chapitre, nous estimons l'effet rebond du transport en véhicule privé en France à partir des données individuelles de ménages pour 2008. Nous utilisons la définition principale de l'effet rebond direct, qui est l'élasticité de l'efficacité de la demande de services énergétiques (Sorrell et Dimitropoulos, 2008). Nous estimons différentes spécifications pour la distance parcourue. Nous corrigeons le biais de sélection de l'échantillon qui résulte du nombre différent de véhicules disponibles pour chaque ménage. De plus, nous simulons un régime fiscal dynamique et discutons de ses implications sur le comportement des voyageurs.

Cette analyse empirique est réalisée avec des données micro-économiques provenant de l'Enquête nationale sur les transports et les déplacements 2007-2008 (ENTD) en France. Cet ensemble de données a été obtenu via la Difussion Quételet-PROGEDO, un portail d'accès aux données françaises en sciences humaines et sociales. Les prix de l'énergie sont tirés de la base de données Pégase ³.

Les résultats montrent l'existence d'un effet rebond au niveau national et dans les zones

³Pétrole, Électricité, Gaz et Autres Statistiques de l'Énergie.

urbaines et rurales en dehors de Paris. Les estimations suggèrent qu'à moyen terme, entre 15 % et 18 % des gains provenant des améliorations de l'efficacité énergétique sont perdus en raison d'une augmentation de la demande de conduite, connue sous le nom d'effet rebond direct. Il semble que les effets de rebond soient sensibles à l'hétérogénéité des ménages. On constate qu'il y a un effet de conservation (rebond négatif) à Paris. De plus, nos modèles prévoient un effet rebond global positif lorsque la consommation de carburant est inférieure à 17,4 km par litre de carburant (ou de manière équivalente, une consommation de carburant supérieure à 5,8 litres de carburant par 100 km). Pour les ménages possédant plus d'un véhicule, le modèle prédit un rebond positif lorsque la consommation de carburant est inférieure à 12,6 km par litre de carburant (ou de manière équivalente, une consommation de carburant supérieure à 7,9 litres de carburant par 100 km). Enfin, la simulation d'une taxe kilométrique intelligente, dont les taux varient en fonction de l'efficacité énergétique et de l'unité urbaine, suggère que l'effet rebond peut être neutralisé lorsque le niveau de taxes sur les carburants sont deux fois plus élevées que celles de 2007/2008.

Chapitre 2. Effet rebond dans le ménage collectif

Ce chapitre examine comment l'hétérogénéité des préférences entre les différents ménages affecte les décisions de consommation d'énergie des ménages. Nous proposons un modèle de ménage collectif qui permet des préférences hétérogènes au sein du ménage. Nous modélisons la demande de services énergétiques et analysons comment les préférences hétérogènes affectent la demande de ces services et l'effet de rebond. Nous utilisons les données françaises sur les dépenses des ménages pour tester notre modèle.

Le présent travail amplifie le cadre théorique actuel, en incluant le ménage collectif et la dimension de bien public telle que présentée par Cherchye et al. (2012). En particulier, nous considérons les préférences hétérogènes au sein du ménage ainsi qu'entre elles, nous modélisons la consommation d'énergie au sein d'un ménage comme un bien public et nous mesurons l'effet de rebond direct. Cette nouvelle méthodologie permet de mieux appréhender l'impact des hétérogénéités sur les comportements de rebond. À notre

connaissance, parmi les quelques travaux théoriques abordant la microéconomie derrière l'effet de rebond (par exemple, Hunt and Ryan, 2015), aucun d'entre eux n'inclut la dynamique intra-ménage dans le modèle. De plus, nous utilisons les données françaises sur les dépenses des ménages pour tester notre modèle.

Nous utilisons des données micro-économiques françaises issues de l'Enquête Budget de famille de 2011. Cet ensemble de données a été obtenu via la Difussion Quételet-PROGEDO, un portail d'accès aux Données françaises en sciences humaines et sociales.

Les résultats du modèle théorique suggèrent que le processus de décision intra-ménage peut définir la taille de l'effet rebond en fonction des préférences. Une simulation est effectuée pour explorer comment le rebond change lorsque les préférences peuvent différer au sein du ménage. Nous constatons que l'effet rebond direct peut être jusqu'à 54 % plus élevé qu'il ne l'est sous l'hypothèse de préférences unitaires. Par conséquent, en ignorant la dynamique intra-ménage, l'effet rebond peut être sous-estimé ou surestimé et l'impact réel des politiques d'efficacité ne peut pas être évalué avec précision.

Chapitre 3. Quand «l'irrigation verte» augmente les émissions de carbone

Généralement, il est admis qu'une technique d'irrigation plus efficace en agriculture permet d'économiser l'eau. C'est ce que l'on peut dénommer «l'irrigation verte». Ce postulat n'est pas constaté dans certains cas. Le but de ce chapitre est d'identifier les facteurs qui assurent le succès de «l'irrigation verte». Notre contribution est de modéliser le coût de l'irrigation, en prenant en compte de l'effet du prix de l'énergie sur la demande en eau. De plus, nous mettons en œuvre un modèle empirique pour tester les résultats théoriques.

Nous avons mis en place une méthodologie qui exploite la variation des charges énergétiques dans notre jeu de données, qui inclut le choc des prix de 2008-2009, pour tester l'effet d'un choc de prix sur la demande d'eau. Nous utilisons pour la fonction de production de l'agriculteur par une fonction paramétrique du type translog avec interactions entre une variable temps et une variable pour le type de système d'irrigation utilisé par

les agriculteurs.

Nous utilisons les micro-données anonymisées du Réseau d'information comptable agricole (RICA). Ces données ont été obtenues à travers le Service statistique ministériel de l'agriculture (Agreste).

Les résultats du modèle théorique présenté dans ce chapitre confirment l'existence d'un effet rebond non seulement de l'eau, mais aussi de l'énergie. Les résultats du modèle empirique montrent un effet coût significatif et négatif pour deux des trois types d'irrigation considérés. Le modèle suggère qu'après un choc des prix, les agriculteurs ayant des retenues collinaires comme source d'irrigation ont réduit leur demande d'eau de 78 % de plus que les agriculteurs du groupe de référence. Les agriculteurs utilisant le pompage en rivière comme source d'eau ont réduit leur demande de 27 % de plus que les agriculteurs du groupe de référence. Nous montrons qu'un effet pervers de l'irrigation verte est l'augmentation de la consommation d'énergie. La source de cette énergie étant généralement non renouvelable, l'irrigation verte peut contribuer à l'augmentation des émissions de gaz à effet de serre.

Conclusion

Le niveau de réchauffement actuel à 1°C a déjà modifié les populations, les moyens de subsistance et les écosystèmes naturels partout dans le monde. La planète a été confrontée à des événements météorologiques extrêmes, la perte de la biodiversité et l'élévation du niveau de la mer, supposant un risque sans précédent, en particulier pour les communautés les plus vulnérables. Si le taux de réchauffement actuel n'est pas arrêté, le réchauffement climatique atteindra probablement 1,5 °C dans les 10 à 30 prochaines années, voire plus si les émissions de gaz à effet de serre ne diminuent pas rapidement d'ici 2030.

Malgré les énormes progrès réalisés dans les politiques d'atténuation et d'adaptation au cours des dernières décennies, la rapidité de ces réalisations est toujours en retard par rapport à la progression du réchauffement climatique. Limiter le réchauffement à 1,5°C nécessitera une plus grande échelle et un rythme de changement plus important pour

transformer les systèmes énergétiques, terrestres, urbains et industriels à l'échelle mondiale.

Les politiques d'amélioration de l'efficacité constituent un pilier important de l'atténuation et de l'adaptation au changement climatique. Elles ont été déterminantes dans la réalisation des objectifs 2020 en UE. Du côté de l'atténuation, les politiques d'efficacité énergétique visent à réduire les émissions de carbone provenant de l'utilisation des véhicules et de la construction résidentielle.

Du côté de l'adaptation climatique, les politiques d'efficacité ont été appliquées à l'eau d'irrigation pour éviter l'épuisement de l'eau. C'est dans ces secteurs que nous trouvons le plus grand potentiel d'économies.

Cependant, la littérature économique a observé l'existence de l'effet rebond, un résultat involontaire résultant d'ajustements de comportement individuels suite à une amélioration de l'efficacité. L'effet rebond peut diminuer l'efficacité des stratégies d'atténuation et d'adaptation basées sur des améliorations d'efficacité.

L'évidence de l'effet rebond a été trouvée dans l'utilisation des véhicules et dans les services énergétiques résidentiels. Avec une perte d'efficacité allant de 5 % à 25 % dans le carburant des véhicules, dans certains pays européens, elle peut atteindre 80 %. Pour le chauffage d'habitation, ces estimations se situent entre 30 % et 70 %.

En agriculture, les résultats empiriques montrent que les programmes d'amélioration de la technologie d'irrigation ont des effets ambigus sur l'utilisation de l'eau et ne réduisent pas systématiquement la demande en eau. Certains ne trouvent pas de preuve d'un effet rebond, tandis que d'autres trouvent un rebond entre 64 % et 100 %, principalement en raison d'une augmentation des terres irriguées.

Dans ce cas cependant, il y a plus d'éléments en jeu. La demande en eau peut également diminuer en raison des coûts énergétiques plus élevés liés à un système d'irrigation plus efficace, et ceci au détriment des émissions de gaz à effet de serre plus élevées provenant de l'augmentation de la demande d'énergie.

Cette thèse apporte un certain nombre de contributions à la littérature, d'un point de vue théorique et empirique, au niveau micro-économique.

Nous testons la sensibilité des estimations de l'effet rebond à la méthodologie. Nous avons proposé une nouvelle méthodologie qui tient compte du potentiel biais de sélection des ménages à plusieurs véhicules. Nous apportons des preuves supplémentaires de l'existence de rebonds hétérogènes qui dépendent du nombre de véhicules et du niveau d'efficacité des véhicules (effets quadratiques).

Nous avons proposé un nouveau cadre théorique, basé sur la théorie du ménage collectif, pour estimer l'effet rebond en tenant compte des préférences hétérogènes au sein d'un ménage. Nous apportons une preuve supplémentaire de l'importance de l'hétérogénéité dans la mesure du rebond.

Nous fournissons des preuves supplémentaires de l'existence d'effets indirects de rebond croisés sur les ressources présents dans le secteur de l'agriculture. En contrôlant le niveau d'efficacité, nous montrons que les agriculteurs utilisant une technologie d'irrigation plus efficace réduisent leur consommation d'eau, cependant, ce n'est pas le résultat d'une efficacité plus élevée mais une conséquence des charges énergétiques plus élevées qui y sont associées. Cela apporte une preuve supplémentaire sur le lien eau-énergie et l'existence de ce que nous avons appelé des effets de rebond inter-ressources.

Quatre résultats politiques clés sont tirés de cette thèse.

Premièrement, les individus (ménages et agriculteurs) adaptent leurs décisions de consommation après un changement majeur, par exemple, une amélioration de l'efficacité qui modifie les prix relatifs. Cela peut aller à l'encontre des résultats attendus des politiques d'atténuation et d'adaptation au changement climatique. Ce qui pourrait expliquer pourquoi les objectifs des politiques climatiques 2020 n'ont été pas atteint dans certains secteurs comme les transports et l'agriculture.

Deuxièmement, ces ajustements ne sont pas homogènes entre les ménages. Leur réponse dépend des caractéristiques de leurs appareils consommateurs d'énergie (par exemple, du

véhicule) et des caractéristiques socio-économiques telles que la zone géographique, le revenu ou l'âge.

Troisièmement, il existe actuellement dans une certaine mesure une incompatibilité entre les politiques d'adaptation au climat, telles que celles qui visent à générer des économies d'eau, et les politiques d'atténuation du climat, celles qui visent à réduire les émissions de CO₂. Jusqu'à présent, les politiques d'adaptation ont montré des résultats prometteurs en matière d'économies d'eau, mais ceux-ci ont été atteints au détriment des objectifs d'émissions de CO₂.

Quatrièmement, la conjoncture économique est importante. Dans le cas de l'agriculteur, les chocs de prix modifient leurs coûts de production qui peuvent modifier l'impact des politiques environnementales sur la conservation de l'eau.

Nos recommandations finales en matière de politiques publiques peuvent être résumées en cinq points.

Afin d'atteindre les objectifs climatiques fixés dans l'accord de Paris, les politiques d'atténuation du changement climatique doivent être conçues de concert avec les politiques d'adaptation au climat afin de maximiser leur impact au lieu de le neutraliser. Les décideurs devraient mieux coordonner les objectifs des politiques environnementales en matière d'eau et d'énergie.

La conception des politiques doit tenir compte des ajustements potentiels du comportement, à savoir l'effet rebond, qui peuvent réduire l'impact positif sur l'environnement. De plus, les politiques d'efficacité devraient être associées à des mesures complémentaires, telles que des taxes différenciées ou des réglementations sur les ressources, afin de contrer l'effet rebond et d'atteindre le résultat environnemental souhaité.

En outre, les politiques devraient tenir compte de l'hétérogénéité. Des politiques mieux ciblées peuvent maximiser l'impact positif sur l'environnement tout en équilibrant la charge supportée par les citoyens. Les instruments uniques n'ont généralement pas la même force et peuvent, en fin de compte, contribuer au problème généralisé d'acceptabilité des poli-

tiques publiques.

Aussi, les décisions politiques doivent être adaptées à la situation économique. Les périodes de crise, comme l'actuelle, contraignent les individus à changer de comportement et à adapter leurs préférences.

Finalement, le succès des politiques climatiques est une question de comportement et d'acceptabilité. Un résultat majeur de la thèse est la mise en évidence de manière théorique et empirique de l'importance de la prise en compte de l'hétérogénéité individuel. Aussi, pour améliorer l'efficacité des politiques, il est crucial que la politique puisse cibler les profils individuels. Ce ciblage permettrait d'optimiser les effets de la politique et d'augmenter son acceptabilité.

D'un point de vue pratique, ces politiques peuvent inclure des politiques incitatives comme des taxes différenciées, ou des politiques plus comportementales, comme la diffusion ciblée d'information sur les effets du changement climatique au quotidien.

General Introduction

The first quarter of 2020, the world shook in face of a ravaging pandemic. Half of the world population was in lockdown, while governments tried to put a halt to the virus spread. After only two weeks in lockdown, air quality improved. One year after the first measures, the CO₂ emissions dropped at a level that may actually allow the European Union (EU) in achieving the 20% energy target by 2020 (EEA, 2020b). Not surprisingly, CO₂ emissions are directly linked to economic activity, which is why the highest reductions in carbon emissions coincide with periods of economic crisis. Nevertheless, once activity recovers, the increasing trend picks up again (Pindyck, 2020).

The scale of the human influence on the planet is such that many scientists consider that the Earth is transitioning into a new geological epoch, significantly shaped by human choices and action, call the Anthropocene. Activities such as industrial processes, fossil fuel combustion and deforestation have led to an average temperature increase of 1°C above pre-industrial levels . The rise in the global concentration of CO₂ is about 20 ppm (parts per million) per decade since 2000, which is faster than any rise in CO₂ registered during the past 800 000 years (IPCC, 2018; Von Weizsacker, 2009).

The current warming level has already altered people, livelihoods and natural ecosystems all around the world. The planet has faced extreme weather events, biodiversity loss and sea level rise cause unprecedented risks, specially to the most vulnerable communities. Global warming is likely to reach 1.5°C in the next 10 to 30 years if it continues to increase at the current rate. What is more, the latest *Emission Pathways* estimated by the Intergovernmental Panel on Climate Change (IPCC, 2018) project that warming may

surpass 1.5°C in the following decades if Greenhouse Gas emissions (GHG) do not decline rapidly by 2030.

In recent decades, enormous progress has been made. The ratio between GDP and CO₂, defined as carbon intensity, has significantly drop over the last 50 years in all over the world. Technological improvement has made production less energy intensive, and therefore, lower amounts of carbon are released (Pindyck, 2020). This technological progress has also been passed over to the consumption side, by increasing the efficiency of energy consuming devices used by households everywhere. In fact, efficiency improvement policies have guided much of the climate change action and progress.

Increasing a system efficiency is often seen as a cost-effective way to reduce intensive use of natural resources. This strategy constitutes an important pillar of climate change mitigation and adaptation. According to the European Environmental Agency (EEA), mitigation policies aim at decreasing carbon emissions linked to human activities. These policies are mainly directed at energy production and consumption, for instance the development of green energies on the production side or the development of more efficient (less energy-consuming) vehicles and residential buildings on the consumption side.

Climate adaptation policies are designed to help societies, economic sectors or ecosystems to better cope with climate change consequences. The impacts of climate change have already begun to manifest in the form of severe weather events, such as drought and floods, which become more frequent as temperatures rise. In this front, efficiency improvements are at the center of water conservation policies, mainly in the agricultural sector.

While progress is undeniable, the speed of these achievements is still behind the progression of global warming. Limiting warming to 1.5°C as aimed by the Paris Agreement on climate change of 2015, will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally (IPCC, 2018).

Paradoxically, the very efficiency policies that have boosted some of the climate related achievements, may have contributed to the overall slow progress. Technical improvements do not necessarily imply resource savings. Economic literature has observed adjustments

in producers and consumers behavior after such improvements, which often results in increased demand for the resource, an opposite effect to that intended by the policy. The increase in demand following an improvement in the technical efficiency of a resource conversion device, is known as the Jevons paradox or rebound effect (Font Vivanco et al., 2018; Steren et al., 2016).

The most documented case of rebound effect is that of private vehicle use. Governments all over the world have implemented policies aiming at reducing the use of fuel by increasing the fuel efficiency of motor vehicles. When a vehicle benefits from an efficiency improvement, individuals can drive the same distance with less fuel. It means that the real price of driving drops and they have now a supplementary income. These new found income is usually spent in more driving. The final gains in fuel are therefore lower due to the rebound in the demand for driving (Sorrell, 2012; Steren et al., 2016).

Another well documented case of the rebound effect is in residential buildings. Empirical evidence shows that the gains calculated by the policy and those effectively observed differ significantly. The efficiency improvement alters the perceived cost of comfort and may thereby generate shifts in consumption patterns. As such, rebound effects are determined by household characteristics such as income (Aydin et al., 2017).

On the production side a similar result is observed. Recent literature has shown the existence of rebound effects in irrigation water in Agriculture. Once again, farmers would adapt their production behaviors, which may result in higher water demand. However, being on the side of production, the rebound effect on irrigation water differs in some aspects from the one described before. Aside from water, other resources are required for agricultural production, namely energy and land (Sears et al., 2018), which creates a relationship among these resources. Particularly, this indicates a crossing point between climate mitigation and adaptation policies.

At the end, climate change policies, such as the efficiency improvement of any device, can be reduced to a problem of resource management. However, individuals respond to these policies by adapting their behavior, which leads to unintended results.

This thesis aims to shed some lights into the rebound effect related to the use of energy (fuel and residential) and irrigation water. This work relies on theoretical and empirical methods to provide three analysis on efficiency improvement policies in France. Furthermore, this thesis draws a policy analysis in the interconnectedness of mitigation and adaptation efforts and how they fit together into the overall panorama of climate change action.

The reminder of this introduction motivates the main research questions addressed in this thesis. Section 1 presents recent figures on climate change and GHG emissions in EU, mainly focused on transportation, residential and agricultural sectors. Section 2 summarize the environmental policies that rely on efficiency improvement in the EU. Section 3 defines the rebound effect and presents some key findings from the recent literature. Finally, section 4 describes the structure of this thesis.

1 Main vectors for global warming

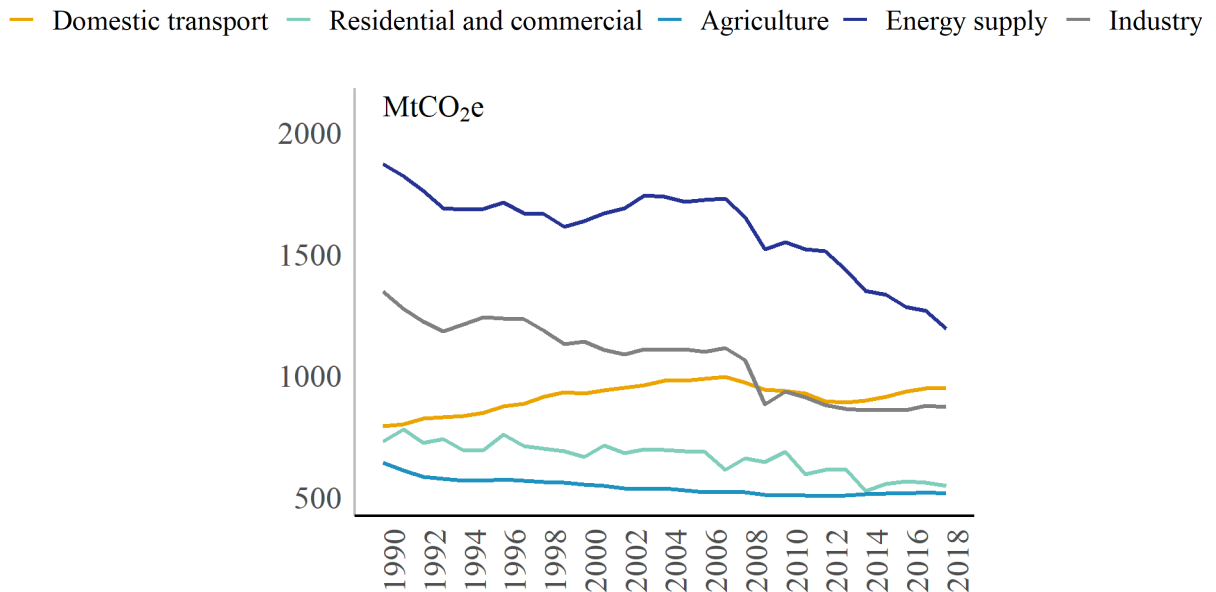
This section focuses in discussing the contributions to GHG emissions of the three sector that emit the most (after energy supply and industrial sectors): Transportation, residential and agricultural sector.

Figure 3 presents the evolution of all GHG emissions (in Millions of tons CO₂ equivalent) in the EU and the United Kingdom between 1990 and 2018 for the five most emitter sectors⁴.

The main takeaways from this figure are that: 1) Emissions (specially CO₂) have steadily decreased since the early 90's; 2) All sectors have contributed positively to this trend except for Domestic Transportation, which exhibits an increasing trend until 2008, when it actually surpasses industrial emissions; 3) Residential and Agriculture sectors show a less pronounced decreasing trend. Overall, this suggests that the potential for savings is the greatest in these three sectors.

⁴Emissions accounted according to the Common Reporting Framework of the United Nations Framework Convention on Climate Change (UNFCCC), see Glossary.

Figure 3: Greenhouse gas emissions by main sector in the EU-27 plus United Kingdom



Reading Note: Each curve represents the evolution in GHG emissions for the period 1990-2018 by sector in millions of tones CO₂ equivalent. The sectoral aggregations correspond to the Common Reporting Framework of the United Nations Framework Convention on Climate Change (UNFCCC, See Glossary).

Source: EEA (2020a).

In the transportation sector emissions have been continuously on the rise since 1990, except for a while during the 2008-2009 economic crisis. This trend is observed in spite of many of the climate policies being directed at passenger and freight transports and the deployment of less carbon intensive and more efficient vehicles on the market. The recent trend may be explained due to consumption patterns of passenger vehicles. This type of vehicles accounts for over half the emissions in this sector. One reason may be that in the EU, in average, bigger cars are being sold and the level of CO₂ emissions per km among those new vehicles is greater (EEA, 2020a).

We will probably observe a decline in emissions for 2020-2021 as a result of the slowdown in the economic activity during the pandemic. However, this effect may not be long-lasting and we could even see a surge in emissions from personal transportation. According to the ITDP (2021), after an initial slowdown in private vehicle use, traffic is surging again all around the world, in some cases achieving higher levels than those observed pre-pandemic.

In the face of a possible infections, individuals found them-selves privileging the use of private vehicles. In some wealthy countries, vehicle purchases have actually increased.

In the residential sector, the improvement in insulation standards in buildings coupled with a less carbon-intensive energy use have lead to a decrease in the demand for space heating in the EU since 1990. In 2016, the residential sector make up for a quarter of final energy consumption⁵ in the EU and demand is expected to rise by 2040.

As such, the observed trend in those sectors represents a challenge for the achievement of the 2030 targets (EEA, 2020a).

Agriculture sector differs from the other two as its connection with global warming is more complex. First, this sector is subject to climate mitigation policies because energy use in agriculture account for over 12% of emissions in the EU (Figure 3).

Second, it needs climate adaptation policies, since water is an essential input in agriculture and water stress episodes are more frequent with climate warming. Agricultural use of water for irrigation accounts for 70% of water use worldwide and 59% in the EU in 2017. Thus, this sector puts the most pressure on renewable freshwater resources. This problem becomes more urgent as population continues to grow and climate change accelerates. Therefore, this sector has been subject a different set of environmental policies, mainly in favor of water economies.

2 Which policies to tackle climate change?

Efficiency improvements policies are at the core of climate action, as a strategy of climate change mitigation and adaptation. Increasing the systems efficiency is seen as an cost-effective way to reduce the intensive use of natural resources.

On the mitigation side, in 2007 the EU set the 3 key targets for 2020: 20% cut in GHG with respect to to 1990 levels, 20% of EU energy from renewables and 20% improvement in energy efficiency. This was part of the strategy to achieve a 55% net reduction in GHG

⁵Households' energy use for space and water heating, space cooling, cooking, lighting and electrical appliances and other end-uses, excluding transportation.

emissions by 2030 and to a climate-neutral EU by 2050.

Improvement in energy efficiency has been a determinant factor in the achievement of the 2020 targets, mainly through the decreasing of carbon emissions from vehicle use and residential buildings, the sectors where the potential for savings is the greatest (IEA, 2020).

In 2009, the EU introduced the first mandatory CO₂ emission standards for passenger cars and light-commercial vehicles. They set a 2015 target of 130 gCO₂/km for the fleet average of all manufacturers combined. This policy has had noticeable results. The average CO₂ emission level of new cars dropped from about 160 gCO₂/km in 2006 to 132 gCO₂/km in 2012 (ICCT, 2014). In 2012, the new target for passenger cars in 2020 was set at 95 gCO₂/km.

On the adaptation side, efficiency measures have been applied to irrigation water for preventing water depletion. The EU's Roadmap to a Resource Efficient Europe 2011 included a goal for 2020, water abstraction should stay below 20 % of available renewable freshwater resources.

Water abstraction and water use in Europe decreased by 17% between 2000 and 2017, while total gross value added generated from all economic sectors increased by 59%. This suggests a decoupling trend during that period, although specific regional and country results may differ greatly. This positive trend is the result of technological improvements in the water use efficiency of appliances, water pricing policies and the socio-economic transition in eastern Europe (AEE, 2019).

Some preliminary estimates suggest that European irrigation efficiency is between 50% and 70%. It means that between a third and half of the water used in irrigation is lost during transportation to the plot, due to evaporation or run-off. This implies that there is still room for improvement in irrigation efficiency (AEE, 2019). Subsidies programs are implemented by governments in order to promote the so called the use of more efficient irrigation technologies (EC, 2011).

According to the latest report IPCC (2018), national programs on mitigation and adaptation are not enough to limit warming to 1.5°C as was stated in the Paris Agreement of 2015. The pace of the change is not as fast as the temperature increase.

Part of this lag may be explained by looking into the efficiency policies. Economic literature has observed the existence of the rebound effect, an undesirable result arising from individual behavior adjustments following an efficiency improvement.

When an energy system becomes more efficient, the real cost of unit energy service may fall. In such case, people would have incentives to consume more energy services, thus increasing the demand for energy. This increase in the demand for energy, or rebound effect, will determine the actual effectiveness of these policies at reducing energy consumption and the associated GHG emissions (Sorrell et al., 2009). This may give some insight into why emissions in the transportation sector continue to increase while vehicles are becoming more fuel efficient.

The UE did not meet the 2020 target of 95 gCO₂/km. In 2019, average emissions from new cars were 122.4 gCO₂/km. In average bigger cars are being sold, hence the higher level of CO₂ emissions per km among those new vehicles. Furthermore, energy consumption began an increasing trend in transport and buildings after 2014, which is the period of economic recovery from the financial crisis (EEA, 2020a).

Similarly, improvements in irrigation technologies may lead farmers to increase their demand for water. Recent literature has pointed out that the introduction of more efficient irrigation systems may actually increase water catchment depletion. In this case, there are some more elements at play. The improvement of an irrigation system lower the real unit cost of water service, but also may improve the productivity of crops and increase the energy charges.

The next section offers a formal definition of the rebound effect, lay down the main difference between energy and water rebound effects and presents some key findings from recent literature.

3 Rebound effect induced by efficiency improvements

The rebound effect is also known as the Jevons' Paradox, named after William Stanley Jevons. He was the first to observe the unintended consequences of efficiency improvements back in 1865 with the Watt steam engine. Jevons showed that the improvement in the efficiency of coal-fired steam engines led to an increase in the use of the steam engine across all industries and, therefore, to an increase in the demand for coal. He thought this to be a paradox, since the efficiency improvement was developed to reduce the coal consumption and, instead, the opposite happened (Sears et al., 2018).

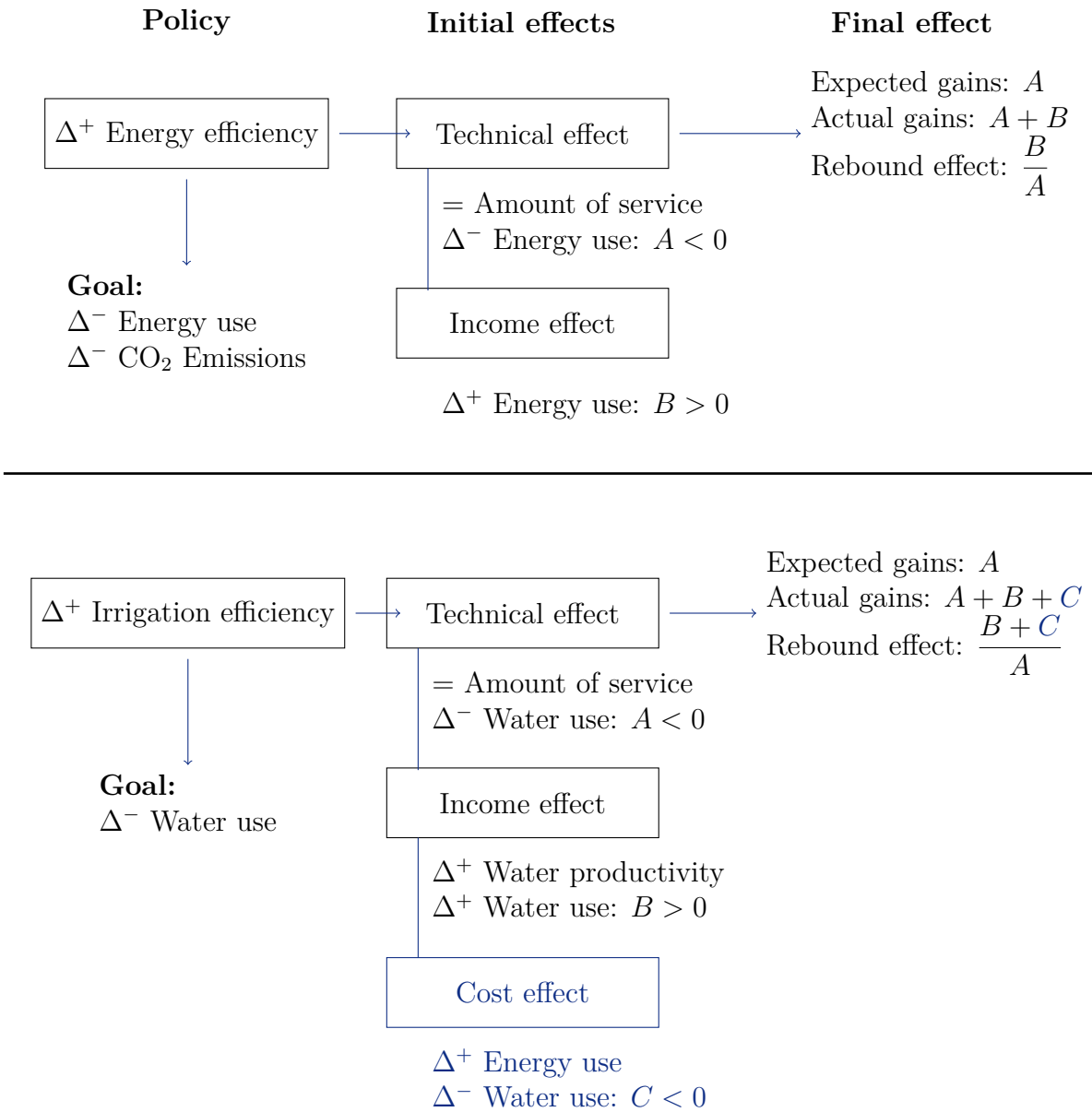
Figure 4 illustrates the mechanisms driving the rebound effect. The first column present the type of policy and its goal. It distinguishes two types of policy goals: a) to reduce CO₂ emissions linked to energy use and b) to reduce water use linked to irrigation in agriculture. The second column show the initial effects, both expected and unexpected, of the policy. The third column shows the final effect of the policy.

The rebound effect can be understood as the consequence of a reinforcing relationship between resource efficiency and resource use. After an efficiency improvement in the process of resource transformation and use, individuals may adjust their response to price changes, which in turn results in a higher demand for the resource (Font Vivanco et al., 2018).

Energy efficiency improvements allow demand to decrease, because the same amount of services can be obtained with less inputs. This corresponds to the technical effect. The gains in resource expected after an efficiency improvement equal the percentage of the improvement, in this case represented by A .

However, the efficiency improvement causes a decrease in the real price of the service, generating a supplementary income, or income effect, B , which drives demand up. In other words, individuals use their supplementary income to increase consumption of all goods and services, including those services that benefit from the initial efficiency improvement. Therefore, the final gains from the policy are reduced by B . The rebound

Figure 4: Mechanism of the rebound effect in energy and water use



Reading Note: Energy efficiency improvements allow demand to decrease, because the same amount of services can be obtained with less inputs (technical effect $A < 0$). However, this causes a decrease in the real price of the service (income effect $B > 0$), which drives demand up. The final gains from the policy are reduced by the rebound in demand. Similarly, when an irrigation technology is improved, we observe the technical and income (productivity) effects. Additionally, there is a cost effect ($C < 0$) associated with the use of energy in irrigation. This effect induce a decrease in demand. The final gains in water may be greater or lower than expected, depending on the size of the productivity and cost effects.

effect is quantified as the percentage deviation from the initial expected gains (ratio B/A) (Sorrell, 2012).

Take for instance, the case of the efficiency targets fixed by the EU. In 2012, the EU set the 2020 target for passenger cars at 95 gCO₂/km. This is equivalent to a reduction of over a quarter of gCO₂/km or an efficiency improvement of the same amount. The European Commission estimated that compared to 2015, fuel consumption will decrease roughly by the same percentage, meaning that $A = -25\%$. This would save 160 million tons of oil between 2020 and 2030, equivalent to 420 million tons of CO₂ less during the same period.

The efficiency improvement will reduce the real price of driving, since the same distance can be driven by using less fuel. Assume that fuel demand increases by $B = 4\%$ between 2020 and 2030, the gains from fuel efficiency (measured in terms of fuel consumption) would be 21% instead the expected 25% and the rebound effect will be $4\%/25\% = 16\%$.

A similar mechanism is at play when improving irrigation systems in agriculture. The improvement in efficiency lowers the needs in water, which decreases water charges: the same area can be irrigated with less water (technical effect A). Furthermore, water applied more efficiently increases crop productivity and yield, which may induce changes in the individual behavior of farmers (income/productivity effect B). They may have incentives to use more water either by irrigating new agricultural areas or by cultivating more water-intensive crops (Li and Zhao, 2018).

Moreover, because the operation of any irrigation system requires the use of energy, the rebound effect in irrigation has an additional impact. An irrigation system constitutes an energy intensive production factor in agriculture. More efficient irrigation systems are usually linked to a more intensive use of energy. Therefore, aside from the technical and the productivity effect described above, an improvement in irrigation technology will create a cost effect (C), associated with the use of energy, which have a negative impact on water demand (Gómez and Pérez-Blanco, 2015).

The final impact of water conservation policies has to account for these three effects. It can be either greater or lower than anticipated, depending on the size of the productivity and cost effects. However, whenever the new technology is more energy-intensive, there

will always be a rebound associated to the use of energy. In other words, there is a cross-resource rebound. This implies that water and energy use in agricultural are closely related.

Now, take a service s that requires a given resource (i.e. water or energy) to be produced. Literature distinguishes three types of rebound effects arising from the decrease in the price of service s after an improvement in the efficiency. A *direct rebound effect* occurs when the consumption of service s increases. An *indirect rebound effect* occurs when the price variation causes changes in demand for *other* goods and services intensive in the same resource. This is mostly observed with energy efficiency improvements. Lastly, an *economy-wide rebound effect* occurs when the fall in the price of service s is followed by changes in prices of intermediate and final goods and quantity adjustments throughout the economy (Sorrell and Dimitropoulos, 2008).

The direct rebound effect is estimated as the efficiency elasticity of the service s . The indirect rebound effect is estimated as the elasticity of good and services other than s to changes in the efficiency of s . Finally, the economy-wide rebound effect represents the sum of the direct and indirect effects (Sorrell, 2012).

The remainder of this section presents the main results drawn from the literature on the rebound effect in fuel demand, residential energy demand and water demand.

Different empirical strategies of estimation

Some studies estimate the rebound based in single-energy service models. This methodology is widely use in the estimation of the direct rebound effect in road transport, the energy service for which we find the most estimates of this effect (Sorrell et al., 2009). These studies focus exclusively on direct rebound effects and neglect the indirect rebound effects.

For motor vehicles, the rebound effect is typically quantified as the percentage change in kilometers (miles) traveled caused by a 1% increase in fuel economy. In other words, the efficiency elasticity of traveled distance. However, due to data availability, the literature

mostly relies on alternative definitions such as the fuel price elasticity of the demand for driving or the own price elasticity of fuel (Sorrell and Dimitropoulos, 2008). The approximation of the rebound effect by the commodity price elasticity can introduce some bias to the measure, especially in the presence of substitutes. This is because a change in efficiency only affects a particular service, whereas a price variation will affect all related services. Nevertheless, the lack of data makes of this method the best approximation for the size of the rebound (Freire-González, 2017).

The existence of the rebound effect in the use of the private vehicle is widely accepted. The estimated magnitude vary widely depending on the type of data or the methodology. Most of the studies based in the United States (US) data find evidence that the rebound effect of increased fuel efficiency on vehicle travel is small, being from 5 to 25% (Greene, 1992; Greene et al., 1999; Small and Van Dender, 2007). However, Linn (2016) finds a rebound effect that erodes about one third of the fuel savings.

In European countries there are fewer works and estimates are less conclusive. Rebound estimates are relatively higher than those in the US, going from 9% to 80% (Frondel and Vance, 2013a; Stapleton et al., 2016; Weber and Farsi, 2014). Estimations made in developing economies, such as China, tend to show greater rebound effects and even in occasions a "backfire effect" (greater than 100%). It means that improving efficiency of traffic service can hardly realize energy conservation (Lin and Liu, 2013; Wang et al., 2012; Zhang et al., 2017).

Other studies include multiple services in the modeling of the rebound effect, namely, by estimating a household demand model. This methodology has the advantage that it allows to measure the direct and indirect rebound effects, by estimating the own and cross-price elasticities for a given energy service.

Rebound effect under household heterogeneity

Even if there is no consensus regarding the size of the rebound effect, researchers agree on the fact that households heterogeneity plays an important role in the size of this ef-

fect. Indeed, households' energy consumption is closely related to socio-economic factors such as income level, expenditure patterns, age or residential environment, since these characteristics determine households' possibility of switching to more efficient technologies. Furthermore, lifestyle and particular needs (e.g. needs of children and elderly family members) can equally affect the energy consumption. Therefore, different household profiles have different capabilities to adapt their consumption choices. A model that do not account for such heterogeneity would misspecify effects and, presumably, generate results with restricted validity.

Recent findings estimate that 40% of energy consumption in the residential sector is determined by technical factors and about 33% is determined by socioeconomic characteristics such as revenue, household age, and tenure status (Bakaloglou and Charlier, 2019). Therefore, the analysis of the effect that individual preferences have on energy demand can shed some lights into the importance of household heterogeneity and the variability in energy consumption. This is especially relevant, given the magnitude of households' demand for energy.

A key element that lacks in the modeling of heterogeneous rebound is the existence of different preferences inside a single household. This is mainly explained by the fact that the rebound literature is based on the traditional unitary models. This approach assumes a common set of fixed preferences among household members and maximizes a single utility function constrained by a household budget (hence the name unitary). Under this framework, households act as a single decision-making unit, regardless of the number of household members, and only total exogenous income explains household behavior. Furthermore, this framework cannot account for the public elements in the consumption of energy services (such as heating) within the household (Donni, 2008; Vermeulen, 2002).

Take for instance the case of a two-person household, in which one member upgrades one of its energy devices and he can access to the same amount of energy service s by using less energy, thus making it cheaper. As usual in the rebound effect theory, we have substitution and income effects. Provided that service s have close substitutes in the

household, this individual can substitute them with the new technology. In this case, we would have a direct rebound effect, because the demand for service s increases as a result of an efficiency improvement. Due to the income effect, this individual can also increase the demand for other goods and services, energy or non-energy intensive.

In the collective setting, the household program is subject to a unique household income, but it takes into account the distribution of that income among household members and, therefore, the weight of each persons' preferences in the decision-making process. In other words, the income effect can change the distribution of power among household members, either by balancing out or overcompensating their influence. The mechanisms behind the rebound effect are not straight forward in the collective household model. The negotiation process within the household can significantly change the size and "direction" (positive or negative) of the rebound.

So far, only few studies have attempt to explain household demand for (some) energy services by considering the existence of heterogeneity within the household and none of these studies have focused on the rebound effect. Bargain and Donni (2012), Browning et al. (2013), and Vermeulen and Watteyne (2006) use the collective household theory and household demand models to explain demand for public goods inside the household. They all consider at least one energy service (transports) as a commodity group in their model. They find a significant difference between energy expenditure elasticity for different household compositions, namely between two-member household and single person household lead by a female.

Water rebound effects and the demand for energy

Investing in water-efficient irrigation technology should enable farmers to keep similar crop yields by using less water (Pfeiffer and Lin, 2014a). However, recent literature suggests that the investment programs do not systematically reduce demand for water (Song et al., 2018). Improving efficiency may induce changes in the individual behavior of farmers. They may have incentives to use more water either by irrigating new agricultural areas or by cultivating more water-intensive crops for instance (Li and Zhao, 2018).

Empirical results show that programs of improvement in irrigation technology have ambiguous effects on water use and do not systematically reduce water demand (Lin Lawell, 2016). A few studies analyze changes in water pricing policies in different countries such as China (Song et al., 2018), Spain (Berbel et al., 2015) and the United States (Li and Zhao, 2018). They reveal that water saving policies aimed at improving water productivity are not as effective as expected because of the rebound effects going from 64% to more than 100%, mainly due to an increase in the irrigated land.

On the other hand, some studies do not find a rebound effect in irrigation water (Peterson and Ding, 2005). Others show that the existence of the rebound effect depends on the implementation of restrictive regulations on the use of water and the cultivated land (Berbel and Mateos, 2014; Berbel et al., 2015). The ambiguity of these results can be explained by the interaction of effects explained in the previous section.

The literature shows that the adjustments in water use can be observed not only following an improvement in irrigation technology, but also following a change in the cost of irrigation, namely as a result of higher energy use. Since, more efficient irrigation systems are directly associated with higher energy demand, any variation in the level of irrigation efficiency will have an effect on both water demand and energy demand (Pfeiffer and Lin, 2014b).

The share of energy in farmers' costs can range from 40% to 65%. In some cases, the importance of energy in the cost of irrigation leads farmers to reduce their water consumption even below the water levels required by the crop, which endangers agricultural yields (Rodríguez-Díaz et al., 2011). Espinosa-Tasón et al. (2020) estimate that in Spain, during the period 2005-2013, irrigation efficiency increases by 0.4% and energy consumption per m³ increases by 2.2%.

Water demand may decrease due to the higher energy costs that drive up the total cost of water extraction, and this at the expense of higher GHG emissions coming from the increase in energy demand. Therefore, the energy issue cannot be excluded from the debate on efficient irrigation in agriculture, since this results implies the existence of a

indirect rebound effect taking place as a cross-resource rebound effect.

4 Thesis Outline

This thesis intends to contribute theoretically and empirically to the ongoing discussion about the method of identification and measure of the rebound effect. It is structured in three chapters combining both theoretical and empirical methods to address different aspects of the rebound effect in energy and water use. Furthermore, this thesis encompasses a strong element of public policy, that aims at providing further elements to the discussion and design of climate change policies, specially efficiency improvement policies.

The first two chapters of this thesis analyze climate mitigation policies based in energy efficiency improvements, that are meant to reduce the use of energy in households. The first chapter presents an empirical analysis that compares the different methods used to estimate the rebound effect in the use of the private vehicle. The second chapter proposes a new theoretical framework of analysis for the rebound effect, based on households heterogeneity, that can be used to estimate residential and vehicle use related rebounds. The final chapter adds a new dimension to the discussion by integrating the analysis of climate adaptation policies in agriculture. This chapter evaluates the rebound effect in the use of irrigation water and discusses the implications of the existing relation between climate mitigation and adaptation policies.

Chapter 1 Driving demand and fuel economy: the French case

In this chapter, we estimate the rebound effect for private vehicle transportation in France using individual household data for 2007-2008. We use the primary definition of the direct rebound effect, which is the efficiency elasticity of demand for energy services (Sorrell and Dimitropoulos, 2008). We estimate different specifications for distance traveled. We correct for the sample selection bias that arise due to the different number of vehicles available for each household. Furthermore, we simulate a dynamic tax scheme and discuss its implications on travel behavior.

This empirical analysis is made by using micro-level data from the 2007-2008 National Transport and Travel Survey (NTTS) for France. This dataset was obtained through the Quêtelet-PROGEDO Difussion, a portal to access French Data in human and social sciences. Energy prices are taken from the database Pégase ⁶.

This empirical work suggests the existence of a rebound effect on the national level and in urban and rural areas outside Paris. The estimates suggest that, in the medium-run, about between 15% and 18% of gains from fuel efficiency improvements are lost due to an increase in the demand for driving, known as the direct rebound effect. It seems that rebound effects are sensitive to household heterogeneity. We find that there is a conservation effect (negative rebound) in Paris. Furthermore, our models predict a positive overall rebound effect when fuel economy is lower than 17.4 km per liter of fuel (or equivalently, fuel consumption greater than 5.8 liters of fuel per 100 km). As for households having more than one vehicle, the model predicts a positive rebound when fuel economy is lower than 12.6 km per liter of fuel (or equivalently, fuel consumption greater than 7.9 liters of fuel per 100 km). Finally, the simulation of a smart kilometer tax, with rates varying with fuel efficiency and urban unit, suggests that the rebound effect can be neutralized when tax rates twice as high as those in 2007/2008 levels.

Chapter 2 Rebound effects in the collective household

This chapter investigates how the heterogeneity in preferences among different household individuals affects the household's energy consumption decisions. We propose a collective household model that allows for heterogeneous preferences inside the household. We model the demand for energy services and analyze how heterogeneous preferences affect the demand for such services and the rebound effect.

We use French micro-data on household expenditure to test our model, from the Family Budget Survey (Enquête Budget de famille) of 2011. This dataset was obtained through the Quêtelet-PROGEDO Difussion, a portal to access French Data in human and social

⁶Pétrole, Électricité, Gaz et Autres Statistiques de l'Énergie (Oil, Electricity, Gas and Other Energy Statistics).

sciences.

The results of the theoretical model suggest that the intra-household decision process can define the size of the rebound effect depending on the preferences. A simulation is made exploring how the rebound changes when preferences are allowed to differ inside the household. We find that the direct rebound effect can be up to 54% higher than it is under the assumption of unitary preferences. Therefore, by ignoring the intra-household dynamic, rebound effect estimates can be misleading, either under or over-estimating the effect, and the actual impact of efficiency policies cannot be accurately assessed.

Chapter 3 When "green irrigation" increases carbon emissions

The aim of this chapter is to identify the factors that ensure the effectiveness of "green irrigation". Our contribution is to model the cost of irrigation as a function of the price of energy on the demand for water.

Furthermore, we implement an empirical model to test the theoretical findings. We approximate the farmer's production function by a translog function. We include interaction according to the type of irrigation system used by the farmers. We implemented a methodology that exploits the variation of energy charges in our dataset, which includes the price shock of 2008-2009, to test the effect of a price shock on water demand.

We use anonymized micro-data from the Farm Accountancy Information Network (FADN). The FADN is a survey carried out by the Member States of the European Union. Every year it collects accountancy data from about 80 000 agricultural holdings in the EU 27. The FADN is the only source of micro-economic data that is harmonised and is representative of the commercial agricultural holdings in the Union. These data were obtained through the Ministerial Statistical Service for Agriculture (Agreste).

The results of the theoretical model presented in this chapter support the existence of a rebound effect not only of water, but also of energy. The results of the empirical model show a significant and negative average effect for two of the three irrigation systems. The model suggests that after a price shock, farmers having hillside reservoirs as irrigation

source reduced their demand for water by 78% more than farmers in the reference group. Farmers using river pumping as their water source reduced their demand 27% more than farmers in the reference group. We show that a perverse effect of green irrigation is the increase in energy use. As the source of this energy is generally non-renewable, green irrigation can contribute to the increase in greenhouse gas emissions.

Chapter 1

Driving demand and fuel economy: the French case

This chapter is based on a joint work with Catherine Benjamin. An early version was published in *Économie & Prévision* (2019), 2 (216), pp 115-132.

Parts of this chapter were presented at: the 41st International Association for Energy Economics, Groningen (Netherlands), June 10-13, 2018; the 15^{ème} Conférence TEPP sur l'Évaluation des politiques publiques, Paris, November 26-27, 2018; the Quatrième Conférence Évaluation des politiques publiques, AFSE-DG Trésor, Paris, December 13, 2018.

Energy efficiency improvement is a mechanism used to try to reduce energy consumption. But it may have perverse effects. When the energy performance of a device is improved, the cost of the service decreases, which may encourage individuals to consume a larger amount of this service. The magnitude of this effect, called rebound effect, is still in debate. We measure this effect for individual transport use in France. We show the rebound effect is dependent on the characteristics of the household (income level, geographical location). We simulate environmental taxation policies to evaluate the tax required to neutralize the rebound.

Keywords: Rebound effect, Vehicle miles traveled, Fuel efficiency, Fuel Taxes, Transports

1 Introduction

Taxes are a major component of fuel price throughout the European Union (EU). The level of fuel taxes, as a percentage of the pump price, differs greatly across the countries in the EU with an average of 60% for petrol and 53% for diesel. In France, fuel taxes are among the highest in the EU, 64% on unleaded and 59% on diesel (Eurostat, 2019). Europe's fuel taxes, which at the beginning were originally designed as an energy measure (to decrease dependence on petroleum imports), serve today as an environmental measure.

Fuel taxes provide means for reducing demand by inducing household's behavioral changes with respect to fuel prices, such as drive fewer kilometers or purchase more fuel-efficient vehicles. Hence, public intervention on price signal is aimed to guide people's choices towards more efficient driving of clean vehicles, with all the positive externalities for air quality and CO₂ reduction that follow (OECD, 2010). Hence, French government plans to wean France off fossil fuels via small but regular tax increases. The next tax increase was planned to start on January 1st 2019. However, in the face of the social movements that have gripped France at the end of the year 2018, the French president decided postpone the project.

Motor fuel taxes are expected to stimulate demand for more fuel-efficient vehicles (efficiency effect) and to raise the cost of driving, which in turn should reduce driving distance. Nevertheless, the incentives provided by fuel taxes may not be greater enough to reduce carbon emissions in line with policy targets. Meanwhile, political and public forces can perceive those taxes as an increase of the government intervention and can argue their regressive effects, since the burden is greater for lower-income families (OECD, 2010; Sterner, 2012).

As an example, we have the supporters of the yellow jackets movement in France. They protest against the increase in fuel taxes, arguing that this measure will hurt the most people in rural areas. Since they rely more on vehicles for work and transportation compared with wealthier city dwellers, who rely more on public transportation. It suggests

that household's fuel demand depends on factors such as locations characteristics (urban and rural areas where infrastructure differs, for instance in terms of public transport availability), financial capacity as well as limitations arising from their lifestyle (e.g., employment, transportation needs linked to children or elderly family members).

Finally, despite all the proved benefits of efficiency improvements, when an energy system becomes more efficient, its real cost may fall, thus inducing people to travel more, taking back some of the potential fuel savings. This is called the direct rebound effect, which can lead to a significant misestimation of the environmental effectiveness of resource efficiency policies: Efficiency decreases energy consumption while the rebound effect increases end-use energy services, partially offsetting the energy savings (Gillingham et al., 2016; Sorrell and Dimitropoulos, 2008).

The direct rebound effect has received much attention in the literature. While its existence is widely accepted, there is still a disagreement about its magnitude. No consensus has been reached regarding its size or the methodology to measure it. In several OECD countries, existing estimates of the magnitude of bounce effects show partial losses in the order of 20% (they are estimated thrice as high in some European countries) compared to average projected energy savings (estimates range from 10% to 30%) (A. Greening et al., 2000; Gillingham et al., 2016).

The formal definition of the direct rebound effect is the fuel efficiency elasticity of the demand for driving. Due to data unavailability, the rebound effect is usually estimated as fuel price or fuel cost elasticity. The assumption behind the latter approach is that consumers respond symmetrically to changes in fuel economy and fuel prices (symmetry assumption). However, recent evidence (e.g. Frondel and Vance, 2013b; Gillingham, 2018; Linn, 2016) suggests that this restrictive assumption can lead to biased estimates of the rebound effect. Individual's perception on price changes and fuel efficiency are different, the former are more noticeable whereas the latter has a more permanent effect. Second, the availability of substitutes for driving, such as public transportation in Europe or multi-vehicle households, makes that price elasticity is no longer a viable proxy for the

rebound effect, since it would confound price and efficiency effects on driving demand.

Furthermore, fuel economy is correlated to a bundle of attributes, the variation of which can also affect driving decisions. Additionally, households heterogeneity plays an important role in the size of this effect, since driving patterns are closely related to socio-economic factors such as income level, average age, residential environment and lifestyle. A model that does not account for such heterogeneities would likely bias the estimates of the rebound effect and restrict the model validity (Gillingham, 2018; Linn, 2016). Finally, traditionally estimates are based in self-declared distance, a less reliable measure, which can add additional noise to the model (Gillingham, 2018).

Finally, time spent driving or on road can become more important as income and congestion increase, as is likely to happen in future years, in which case the direct rebound effect would decrease (Gillingham, 2018; Sorrell and Dimitropoulos, 2008).

In this chapter, we estimate the rebound effect for private vehicle transportation in France using individual household data for 2007-2008. We use the primary definition of the direct rebound effect, which is the efficiency elasticity of demand for energy services (Sorrell and Dimitropoulos, 2008). We look into the empirical implications of the potential sources of bias presented above by estimating the rebound effect under different model specifications.

Furthermore, we simulate a dynamic tax scheme and discuss its implications on travel behavior. Likewise, we assess the tax rate needed to reduce the amount of kilometers traveled and the rebound effect.

The contribution of this chapter is twofold.

First, this chapter contributes to the growing literature in the rebound effect from a methodological perspective. We estimate the rebound effect in private transport using micro level data for France under seven different specifications. We estimate the rebound by using odometer readings and declared distance. We also compare the estimates by using OLS and by taking into account the endogeneity of fuel economy. Furthermore, we allow for heterogeneity, by adding non-linear effects and by estimating a differentiated

rebound by geographic area. Finally, we correct the selection bias arising when modeling households having different number of vehicles. To the best of our knowledge, this correction has never been addressed in the literature.

Second, this work contributes to the policy debate by discussing the scope of policies to counteract it. We show that the rebound effect is differentiated by geographic zone and level of fuel economy. Our regression results indicate an heterogeneous rebound effect. Taking the example of a fossil fuel tax, we study the tax rate required to neutralize the rebound effect and how this tax rate varies across key model variables (household characteristics, location characteristics).

The rest of the chapter is organized as follows. Section 2 presents a literature review on the rebound effect. In section 3, we expose the theoretical framework and the estimation methods. Section 4 presents the data used in the empirical analysis. Section 5 reports the estimation results from the seven model specifications. Then, section 6 presents the simulation of a kilometer tax and a discussion of welfare implications. Finally, section 7 concludes.

2 Main results of previous studies

Take a service s that requires a given resource (e.g. energy) to be produced. Literature distinguishes three types of rebound effects arising from the decrease in the price of service s after an improvement in the efficiency.

A *direct rebound effect* occurs when the consumption of service s increases. An *indirect rebound effect* occurs when the price variation causes changes in demand for *other* goods and services intensive in the same resource. This is mostly observed with energy efficiency improvements. Lastly, an *economy-wide rebound effect* occurs when the fall in the price of service s is followed by changes in prices of intermediate and final goods and quantity adjustments throughout the economy (Sorrell and Dimitropoulos, 2008). In this chapter, we focus only on the direct rebound effect (hereinafter called rebound effect).

Table 1: Summary of the most relevant and recent studies on the direct rebound effect in private transport

| Study | Estimation | Period | Region | Model/Method |
|--|-----------------------|-----------|--------------------------|---------------------------|
| <i>Estimating the elasticity of travel with respect to per unit fuel costs</i> | | | | |
| Greene (1992) | 5%-15% | 1966-1989 | US | OLS |
| Small and Van Dender (2007) | 4.5% (SR) 20-25% (LR) | 1966-2009 | US | 3SLS |
| Kemel et al. (2011) | 26% | 1999-2007 | France | Dynamic equations |
| Ajanovic and Haas (2012) | 44% | 1970-2007 | 6 countries ^a | Co-integration |
| Greene (2012) | 10% | 1966-2007 | US | Linear lagged adjustment |
| Stapleton et al. (2016) | 9%-36% | 1970-2011 | Great Britain | Static and dynamic models |
| <i>Estimating the elasticity of travel with respect to fuel efficiency</i> | | | | |
| Greene et al. (1999) | 23% | 1979-1994 | US | 3SLS |
| Frondel and Vance (2013b) | 46%-70% | 1997-2009 | Germany | Panel |
| Weber and Farsi (2014) | 75%-81% | 2010 | Switzerland | 3SLS |
| Linn (2016) | 20%-40% | 2009 | US | IV |

a: Austria, Germany, Denmark, France, Sweden, and Italy.

For motor vehicles, the rebound effect is typically quantified as the percentage change in miles (kilometers) traveled caused by a 1% increase in fuel economy. In other words, the rebound effect corresponds to the efficiency elasticity of the demand for driving (Sorrell and Dimitropoulos, 2008).

Due to data unavailability, namely fuel efficiency measures, the literature mostly relies on alternative definitions of the rebound effect such as the fuel price elasticity of the demand for driving or the own price elasticity of fuel (Sorrell and Dimitropoulos, 2008). Table 1 summarizes some of the most relevant and recent estimations of the rebound effect by definition.

Recent research has pointed out that these alternative definitions only hold under a set of restrictive assumptions: (a) they assume that consumer responses to a price decrease

and to an improvement in energy efficiency are symmetric; (b) energy efficiency is taken as constant. However, empirical evidence suggests that these assumptions are not verified due to a number of factors that, if ignored, could lead to biased estimates of the rebound effect and will provide misleading guidelines for future policy development (e.g. Frondel and Vance, 2013b; Gillingham, 2018; Sorrell and Dimitropoulos, 2008).

First, Gillingham (2018) explains that consumers tend to be more aware of fuel prices variations leading to a higher response to fuel prices. On the other hand, Linn (2016) argues that the response to fuel economy may be higher than the response to fuel prices, since the former has a more permanent effect than the latter. Either case, the use of price elasticity may give misleading estimates.

Furthermore, Chan and Gillingham (2015) find that the use of alternative definitions of the rebound effect may be biased when multiple driving options are available (such as multiple vehicles or public transportation). Notice that an efficiency improvement affects only the upgraded vehicle, thus driving becomes cheaper when using that vehicle while the implicit price of other driving option remains constant. On the other hand, a change in the fuel price would affect the implicit price of driving in every driving mode and the estimated rebound effect would not distinguish the source of the demand increase. This is particularly relevant in Europe, where fuel prices are higher and there is a more viable substitute to driving in public transportation.

Moreover, recent literature suggests that fuel economy is endogeneous and is correlated with other vehicle attributes (e.g. Linn, 2016; Stapleton et al., 2016). If individuals expect to drive long distances very often, they would most likely opt for highly efficient vehicles to reduce the cost of driving. In such cases, travel distance and fuel economy would be simultaneously determined. In order to tackle such endogeneity problems, one can include suitable instrumental variables for fuel efficiency or estimating a simultaneous equation model that includes separate equations for the total distance traveled and the fuel efficiency of the motor vehicle fleet (Linn, 2016; Small and Van Dender, 2007; Sorrell and Dimitropoulos, 2008; Stapleton et al., 2016; Weber and Farsi, 2014).

Most estimates of the rebound effect for the United States go from 5% to 20%. Considering only fuel economy elasticity estimates, the rebound effect is placed between 10% and 35%. When using alternative definitions, most estimates suggest an increase in demand between 7.5% and 25%. Regarding European data, there are fewer works and estimates are less conclusive. Most studies suggest a rebound effect going from a modest 12% to a substantial 75%. The estimates seem more sensitive to the country than to the methodology (Sintek et al., 2016). In France, only Kemel et al. (2011) have addressed the endogeneity problem.

Time value increases with income and congestion, meaning that the direct rebound effect may decline with the increase in household income and expenditure (Gillingham, 2018; Small and Van Dender, 2007; Sorrell and Dimitropoulos, 2008). Estimations made in developing economies, such as China, tend to show greater rebound and even in occasions a "backfire effect". It means that improving efficiency of driving can hardly realize energy conservation (Gillingham et al., 2016; Wang et al., 2012; Zhang et al., 2017).

Linn (2016) is one of the most recent and complete estimates of the rebound effect using micro level data for the US. He accounts for several vehicles in the household and for the main source of bias explained above. He finds a rebound effect between 20% to 40%, a rate significantly higher to previous rebound estimates. However, he used a declared measure of distance which can introduce some bias to the estimates (more in section 4) and he does not account for potential sample selection bias arising by the fact that households have different number of vehicles.

This chapter has two main goals. First, we compare several specification used to estimate driving distance and the rebound effect. We want to gauge the sensitivity of rebound estimates to the methodology. Second, we augment the methodology used by Linn (2016), in at least fourth ways. First, we use a measure of distance obtained from odometer readings, which is more accurate. Second, we privileged the use of 3SLS over simple instrumental variable to take into account the joint determination between different vehicles in the household. Third, we allow several types of heterogeneity in the rebound coefficient. Fourth, we control for the potential sample selection bias arising by the fact

that households have different number of vehicles.

3 Theory and Empirical strategy

The theoretical basis of the rebound effect relates to a model of household production with durable goods and energy demand, close to Dubin and McFadden (1984). Demand for fuel comes from households' need for travel, which in turn is a mere means to achieve certain needs or wants (e.g. go to work).

Having in mind the expectations of future use, price trends and own socio-demographic characteristics, households solve an optimization program in which they produce a certain amount of households services, such as driving, with a combination of inputs and a durable conversion device. In other words, they derive their utility from the consumption of the services and not from the sole use of the energy and capital inputs (Davis, 2008; Sorrell and Dimitropoulos, 2008).

In this chapter, we are interested in a particular energy service ¹: *driving*. It is produced with a combination of energy (fuel) and a certain technology (vehicle) of given efficiency level (Chan and Gillingham, 2015). The efficiency level can be measured as the fuel consumption of the vehicle, given by the liters of fuel consumed per kilometer driven. Equivalently, it can be measured as the fuel economy of the vehicle, given by the km driven by liter of fuel. In the case of private car use, the amount of energy service can be measured as vehicle-miles traveled or passenger-miles traveled (Sorrell and Dimitropoulos, 2008).

The reminder of this section presents the theoretical model and the empirical strategy for the estimation of the rebound effect, similar to the methodology in Linn (2016). Notice that, households' decision process consists of a choice of transport mode and, subsequently, the level of demand for the transport mode. In this chapter we focus on the use of the private car, meaning that we only consider households who have chosen their vehicle as the preferred transport mode. Therefore, the results presented here can shed some

¹Services that require a source of energy as a main input.

light on the mechanisms behind the changes in household demand for driving after an improvement in fuel efficiency. However, they cannot predict vehicle ownership or travel mode choices.

3.1 A demand system for vehicle-miles traveled

We consider a system in which Vehicle-Kilometer Traveled (VKT) and fuel efficiency are simultaneously determined. The model takes into account the fuel economy of all household vehicles as in Linn (2016).

We assume that households choose how much to travel accounting for the fuel economy of all their vehicles. Individuals determine fuel economy by accounting for the regulatory environment and their expected amount of driving.

Furthermore, we considered fuel price to be exogenous (Linn, 2016). These assumptions describe the following structural model:

$$\begin{aligned} VKT_{ij} &= f(E_{1j}, \dots, E_{Ij}, P_{ij}, X_j, \zeta_j) \\ E_{ij} &= f(VKT_{ij}, \zeta_j, Z_{E_{ij}}) \end{aligned} \tag{1}$$

Where VKT_{ij} is the traveled distance in km of vehicle i ($i = 1, \dots, I$, where I is the number of vehicles) in household j and E_{ij} is its fuel efficiency level. P_{ij} is a vector of current fuel prices, X_j is a set of exogenous variables expected to affect distance, ζ_j is a vector of socio-demographic characteristics and $Z_{E_{ij}}$ is a set of exogenous variables expected to affect each vehicles' fuel economy (i.e. instruments).

We follow the primary definition of the direct rebound effect given in the previous section. That is to say, the direct rebound effect is given by the efficiency elasticity of the demand for driving or traveled distance. Under the framework presented in here, the rebound effect, associated to vehicle i , can be written as:

$$\eta_{E_i}^{VKT} = \frac{\partial VKT_i}{\partial E_{ij}} \frac{E_{ij}}{VKT_{ij}} \quad (2)$$

Equation (2) represents the efficiency elasticity of demand for traveled distance for one vehicle. The rebound effect for all vehicles in the household is given by the sum of the individual rebound effects. A positive rebound effect can be interpreted as the loss in efficiency gains due to an increase in the demand for driving.

3.2 The demand for driving

We define an equation for the distance traveled VKT , linear in parameters that depends on the fuel economy of all vehicles in the household, current fuel prices and a bundle of household characteristics. All these variables are in logarithmic form.

Following Linn (2016), we allow for differentiated demand response to fuel economy and price changes.

$$\ln VKT_{1j} = \beta_0 + \beta_1 \ln E_{1j} + \beta_2 \ln E_{2j} + \beta_3 \ln Pf_{1j} + X_j + \epsilon_j \quad (3)$$

VKT_{1j} is the travel distance in km of vehicle 1 in household j , measured during a reference week. E_{ij} is the fuel economy of vehicle i (for $i = 1, 2$, where the number of vehicles is $I = 2$) in household j . Pf_{1j} is the average fuel price during the month VKT was measured, X_j is a set of household characteristics and ϵ_j is the idiosyncratic error. VKT has been measured only for vehicle 1, however, we have information about attributes of both vehicles, 1 and 2.

When the household has two vehicles, E_{2j} is the fuel economy registered for the second vehicle and when it has more than two vehicles, E_{2j} acts as a proxy for the average fuel economy of other vehicles in the household.

Considering that this model is design for cross-section data, the coefficient for fuel price represents the short-run response to fuel price changes, not an elasticity. Elasticity estimates require price variations over several years (Sorrell, 2012). Moreover, since households have kept their vehicle 8 years on average, fuel economy coefficients can be interpreted as a response of *longer*-term. Therefore, these coefficients can be read as short-run and medium-run responses respectively (Linn, 2016).

Under the specification from (3), we can compute the rebound effect by number of vehicles, defined as the elasticity of the distance with respect to fuel economy: β_1 , for households having one vehicle and $(\beta_1 + \beta_2)$ for households having more than one vehicle.

Since our goal is to estimate the rebound effect of all vehicles in the household, we compute the sum of the two rebounds previously defined, weighted by the share of households having more than one vehicle noted ω :

$$\eta_E^{VKT} = (1 - \omega)\eta_{E_1}^{VKT} + \omega\eta_{E_2}^{VKT} = (1 - \omega)\beta_1 + \omega(\beta_1 + \beta_2) = \beta_1 + \omega\beta_2 \quad (4)$$

In our sample, the share of households having more than one vehicle (ω) is equal to 40%.

Under the hypothesis that there is a positive rebound effect, we expect E_{1j} to have a positive relationship with VKT_1 . Meaning that households will drive more when their vehicle is more efficient. On the other hand, we expect E_{2j} to have a negative sign, which implies a substitution effect among household vehicles (Linn, 2016). The overall effect (Equation (4)) is expected to be positive.

3.3 Heterogeneous rebound effect

The model described in equation (3) is augmented as to allow for heterogeneous rebound effects and greater heterogeneity between households.

The first specification with heterogeneity is given by:

$$\begin{aligned} \ln VKT_{1j} = & \beta_0 + \beta_1 \ln E_{1j} + \beta_2 \ln E_{2j} + \beta_3 \ln Pf_{1j} + \\ & \beta_4 \ln E_{1j}^2 + \beta_5 \ln E_{2j}^2 + X'_j + \varepsilon_j \end{aligned} \quad (5)$$

This model includes a squared term for fuel efficiency of all vehicles. The vector of household characteristics X'_j now includes the squared income and age to capture non-linear effects on the driving distance, and a variable to account for the vehicles attributes.

In this case, the rebound effect by number of vehicles would be $(\beta_1 + 2\beta_4 \ln E_{1j})$ for households having one vehicle and $(\beta_1 + \beta_2 + 2(\beta_4 \ln E_{1j} + \beta_5 \ln E_{2j}))$ for households having more than one vehicle. The rebound effect of *all* vehicles in the household is computed as defined in (4).

As we can see, the rebound effect would be determined by the level of fuel economy and therefore it would be different for every household. Assuming that the set of coefficients $\{\beta_1, \beta_4\}$ and $\{\beta_2, \beta_5\}$ are significant and have opposite signs, the quadratic effect would be significant and we could estimate the maximal fuel economy, at which point the relationship between VKT_{1j} and E_{1j} inverts.

The second specification with heterogeneity is given by:

$$\begin{aligned} \ln VKT_{1j} = & \beta_0 + \beta_1 \ln E_{1j} + \beta_2 \ln E_{2j} + \beta_3 \ln Pf_{1j} + \\ & \sum_{k=1}^2 (\beta_{4k} \ln E_{1j} + \beta_{5k} \ln E_{2j}) \times D_k + X'_j + \xi_j \end{aligned} \quad (6)$$

In this model, we add interactions between fuel economy and the urban unit, represented by the dummy variable D_k (for $k = 1, 2$) taking the value of 1 when household j is in the geographic zone k , and 0 otherwise. The geographic zones are: Urban areas (not including Paris, $D_1 = D_2 = 0$ - reference zone), Rural areas ($D_1 = 1, D_2 = 0$) and Paris area ($D_1 = 0, D_2 = 1$). With this interaction we allow for household heterogeneity in the

response of driving distance to fuel economy.

In this case, there are two different rebounds for every geographic zone, as shown in table below.

| | D_k | <i>One vehicle</i> | <i>More than one vehicle</i> |
|--------------|-----------------------------|------------------------|---|
| Urban area | $D_1 = D_2 = 0$ (reference) | β_1 | $\beta_1 + \beta_2$ |
| Rural area | $D_1 = 1, D_2 = 0$ | $\beta_1 + \beta_{41}$ | $(\beta_1 + \beta_{41}) + (\beta_2 + \beta_{51})$ |
| Paris region | $D_1 = 0, D_2 = 1$ | $\beta_1 + \beta_{42}$ | $(\beta_1 + \beta_{42}) + (\beta_2 + \beta_{52})$ |

Following (6), the rebound effect of *all* vehicles in the household is computed by geographic area as defined in (4).

3.4 Endogeneity of fuel efficiency

In this section, we detail how to tackle the possible endogeneity of fuel efficiency.

We use 3SLS approach to correct the endogeneity of fuel efficiency, by including instrumental equations for fuel efficiency of all vehicles (E_{1j} and E_{2j}). This approach is privileged over simple instrumental variable because it can take into account the joint determination between different vehicles in the household.

We test three different instruments. A good instrument for fuel efficiency can be an index for the regulation environment concerning fuel demand. Consequently, we use the difference between CO₂ emission standard in Europe for 2009, 130 *g/km*, and the amount of CO₂ emitted by the vehicle. Additionally, we use the fiscal horsepower rating as suggested by recent literature (i.e. Frondel and Vance, 2013a; Linn, 2016). The fiscal horsepower rating depends on vehicle's horsepower and CO₂ emissions, therefore it can be a good proxy of the regulation environment. Finally, following Linn (2016), we use the fuel price at the time the vehicle was obtained as an instrument, due to the strong correlation between fuel prices and vehicle fuel economy.

The instrumental equation for fuel efficiency is defined as:

$$\ln E_{ij} = \gamma_0 + Z_{ij} + X_j' + u_j \quad (7)$$

With Z_{ij} the vector of instruments for vehicle i in the household j . X_j' is a bundle of vehicle and household characteristics acting as their own instruments. u_j is the idiosyncratic error. The vector of instruments Z_{ij} is augmented with interaction and squared terms for the specifications that require it.

3.5 Sample selection on the number of vehicles

As mentioned above, the fact that households have different number of vehicles induces a selection bias in our sample. The variable fuel economy of the second vehicle have some missing entries because a subgroup of households in our sample have only one vehicle. It implies that the households having more than one vehicle can be misrepresented by our model leading to biased results.

The selection bias requires the use of a probit selection equation to assess what motivates a household to have one or more vehicles. Additionally, we are facing a problem of endogenous explanatory variables (fuel economy). To cope with both problems, we follow the methodology describe in Wooldridge (2010).

First, we estimate the following probit model:

$$OV_j = \rho_0 + S_j + \nu_j \quad (8)$$

$$\text{where } OV_j = \begin{cases} 0 & \text{if households have only one vehicle} \\ 1 & \text{if households have more than one vehicle} \end{cases}$$

In this model we include the dummy determining selection, OV_j , and a set of exogenous

variables S_j that may influence the decision of buying a second vehicle. These variables are current and past fuel prices, household characteristics, indexes of mobility patterns and public transportation facilities.

Second, we compute the Inverse Mills Ratios (IMR) and finally, we estimate equations (1), (5), (6) (depending on the case) and (7) for the two subsets of households, including IMR as an exogenous variable. Since IMR depends only on exogenous variables, it acts as its own IV. In this case, we estimate a model without interactions and another with interactions.

4 Data and summary statistics

The empirical analysis is carried out using two data-sets: the 2007-2008 National Transport and Travel Survey (NTTS) and the Pégase² database.

Most of our data comes from the NTTS, which is conducted every ten years by the National Institute of Statistics (Insee) and the Observation and Statistics Service (SOeS) of the Ministry for Ecology, Sustainable Development, Transport and housing (MEDDTL). This database was collected thanks to the Quételet-PROGEDO Difussion, a portal to access French Data in human and social sciences. The aim of this survey is to compile representative and reliable information on French households, their use of individual and collective forms of transportation and the characteristics of their vehicle fleet.

The survey has been conducted over a 12 months period³ in order to capture seasonal travel mobility. It gathers information on households, individuals and vehicles characteristics. In 2007-2008, about 20 200 households were interviewed regarding their everyday transport behavior, gathering almost 45 000 individuals of all age groups.

The NTTS comprises detailed information about vehicles stock (two and four-wheeled) and attributes (fuel intensity, weight, age, horsepower, fuel type, etc.), mobility patterns

²Pétrole, Électricité, Gaz et Autres Statistiques de l'Énergie (Oil, Electricity, Gas and Other Energy Statistics).

³Most visits were made between May 2007 and April 2008. A few visits were made during April 2007.

during a reference week and the last 12 months, long distance and tourism trips. Moreover, it collects information on the household composition and demographic characteristics. We restrict the sample to observations with no missing values in the variables of interest. We consider all households with at least one vehicle. The final sample is composed of 4630 observations. A detailed account on the data cleaning and format process is found in appendix A.

The second data-set corresponds to the monthly domestic fuel price series from the database Pégase. This data is collected by the Data and Statistical Studies Service (SDES) of the Ministry for Ecological and Social Transition (MTES).

Variable definitions

In this section we present the variables used in the subsequent analysis and how they were collected and computed. Table 2 presents a definition of the variables used in the driving demand models.

Table 2 reports two measures of distance: odometer readings and declared. The most common measure of distance or vehicle-miles traveled used in the literature is the declared distance traveled over the last 12 months. Being a declared measure, this variable includes some bias resulting from the approximation (Gillingham, 2018; Linn, 2016). The dataset employed in this analysis includes a variable of distance measured with the vehicle's odometer, which is more accurate.

Figure 1 illustrates a comparison between odometer readings and declared distance. Figure 1a shows the distribution of the distance issued from odometer readings. We can see a perfectly smooth and strongly right skewed distribution. On the contrary, Figure 1b, reporting the declared distance, shows spikes at round numbers.

The odometer readings of the main vehicle were collected as follows. During a first visit, one vehicle of the household (henceforth, vehicle 1) is randomly selected using unequal probability sampling. Then, the driver has to describe every trip made with vehicle 1 during the seven days following the first visit. The driver fills a card with the number of

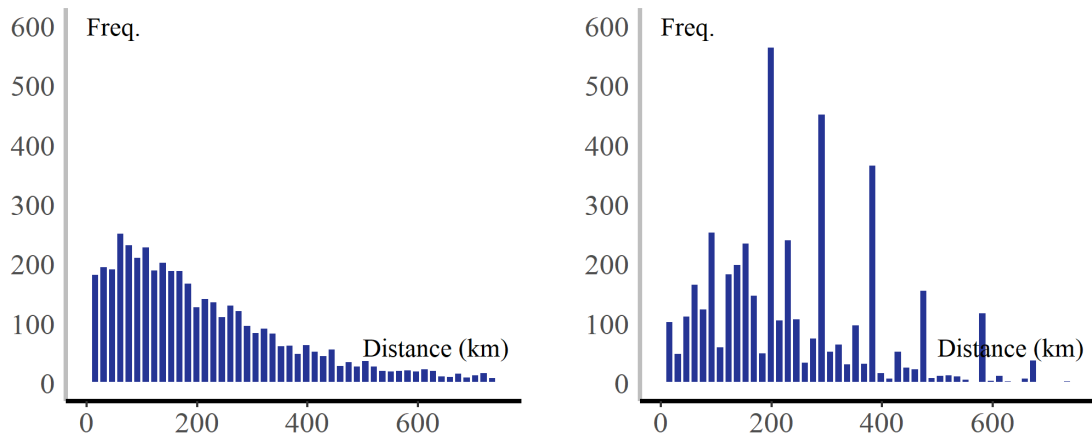
Table 2: List of variables

| Variable name | Definition |
|--------------------------|--|
| Continuous Variables | |
| <i>VKT</i> | Distance traveled vehicle (1) - Odometer |
| <i>VKT^D</i> | Distance traveled vehicle (1) - Declared |
| <i>FEC_i</i> | Fuel economy vehicle (i) in kgoe |
| <i>FCONS_i</i> | Fuel consumption per 100 km of vehicle (i) |
| <i>VHAGE_i</i> | Age of vehicle (i) |
| <i>PRI</i> | Fuel price |
| <i>NBVEH</i> | Number of vehicles in the household |
| <i>DNBUS</i> | Distance to nearest bus/subway station |
| <i>DNTRA</i> | Distance to nearest train station |
| <i>ATMIN</i> | Average trip duration |
| <i>MINC</i> | Monthly income |
| <i>MINC²</i> | Squared monthly income |
| <i>MINCUC</i> | Monthly income adjusted by the household composition |
| <i>AGE</i> | Age |
| <i>AGE²</i> | Squared age |
| <i>HHSIZ</i> | Household size |
| <i>EMPL*</i> | % of active members |
| Dummy variables | |
| <i>VEH2</i> | The household have more than one vehicle |
| <i>DIES_i</i> | Vehicle (i) uses Diesel |
| <i>OPT</i> | Vehicle (1) has options |
| <i>HIGED</i> | <i>Reference: Higher education</i> |
| <i>HIGSC</i> | High School |
| <i>SECSC</i> | Secondary Education |
| <i>PRISC</i> | Primary Education |
| <i>NOSC</i> | No diploma |
| <i>TYP1</i> | <i>Reference: Dispersed households</i> |
| <i>TYP2</i> | Subdivision houses |
| <i>TYP3</i> | Townhouses |
| <i>TYP4</i> | Large complex |
| <i>TYP5</i> | Mixed housing |
| <i>URB</i> | <i>Reference: Urban area</i> |
| <i>RUR</i> | Rural area |
| <i>PAR</i> | Paris region |
| <i>OWN</i> | <i>Reference: Vehicle owned by the household</i> |
| <i>OUT</i> | Vehicle owned by an outsider |
| <i>FIRM</i> | Vehicle owned by the firm |
| <i>OTH</i> | Other |

All continuous variables are in logarithms, unless otherwise specified.

* It is computed as the ratio between the number of active individuals in the household and the household size.

Figure 1: Comparison between odometer readings and declared distance



(a) Odometer readings

(b) Declared

Reading Note: This figure compares two measures of distance. On the left we have the distance measured with the vehicles odometer. On the right panel we have the annual distance declared by the households, convert to weekly average. The latter presents spikes at round numbers, which is known as the heaping-induced Bias.

kilometers displayed on the car’s odometer at the beginning and end of every trip. He also registers the number of passengers and the reason for the trip.

On the same visit, a second random selection is run among all vehicles⁴ in the household. The aim of the second lottery is to *potentially* collect further information (i.e. vehicle’s characteristics such as age, weight or fuel intensity) about a second vehicle within the household⁵.

In summary, as a result of the first lottery we have: (a) a measure for traveled distance collected during a reference week for vehicle 1 and (b) a description of vehicle 1 characteristics. From the second lottery we have: (c) a description of vehicle 2 (only if the vehicle chosen in both lotteries is different).

The endogenous explanatory variables E_1 and E_2 were computed as the inverse of the on-road fuel consumption per 100 km. Knowing that vehicles in the sample use different type of fuels, mainly gasoline and diesel, the energy efficiency measure cannot be directly

⁴Including vehicle 1, the vehicle chosen from the first lottery.

⁵Notice that whenever the vehicles chosen in those two lotteries are different, the survey includes detailed information about both vehicles (1 and 2), but travel distance during the reference week is tracked only for one vehicle (1). Otherwise, the survey contains information about one vehicle: vehicle i .

compared. This is because the amount of energy produced by one unit of diesel is not equivalent to the amount of energy produced by one unit of gasoline. Therefore, following Kemel et al. (2011), we converted this measure of efficiency to a common unit, *Kilograms of oil equivalent* (kgoe), in order to make them comparable (see appendix A).

Monthly fuel prices were deflated to 2008 level and matched to the fuel type (gasoline or diesel) for every vehicle. Current prices are assumed to be exogenous because there is not enough variability during the one year period we consider. Thus, inline with the literature (e.g. Linn, 2016), we expect no significant impact of current fuel prices on traveled distance.

Household characteristics include monthly income and squared monthly income, education level, age of the reference household member, the percentage of household member that is employed (active) and the owner of the vehicle (for instance, company vehicle).

We account for the fact that vehicle use largely depends on infrastructure and availability of transport alternatives. To this end we include the distance from the residence to the nearest public transport facilities (subway, tramway and train). This variable can give us some insight into the role of public transportation for French households. We also compute a geographic variable, by urban area and size of activity center, with three levels: Rural areas, Paris urban area and other urban areas. Furthermore, we consider the type of neighborhood to control for geographical differences at a smaller scale. Finally, we compute the daily average of travel time to account further for mobility patterns.

Summary statistics

Table 3 presents the summary statistics of the main vehicle and household characteristics presented before. The last column of the table presents the average values of some of those characteristics for the French population in 2008. We see that the sample is largely representative of the French population.

For comparison purposes, the declared annual distance was converted to weekly. In average, households in the sample drove 237 km during the reference week. Similar to the

Table 3: Summary statistics

| | Mean | Sample | | | France 2008 |
|--------------------------|---------|---------|-------|----------|-------------|
| | | SD | Min. | Max. | Mean |
| <i>VKT</i> | 236.79 | 222.77 | 1.00 | 2541.00 | 245 |
| <i>VKT^D</i> | 254.77 | 183.70 | 0.00 | 2099.46 | 245 |
| <i>PRI</i> | 1.26 | 0.10 | 1.09 | 1.43 | 1.33 |
| <i>DIES₁</i> | 0.44 | 0.50 | 0.00 | 1.00 | 0.40 |
| <i>DIES₂</i> | 0.42 | 0.49 | 0.00 | 1.00 | 0.40 |
| <i>FCONS₁</i> | 6.73 | 2.09 | 1.00 | 75.00 | 6.98 |
| <i>FCONS₂</i> | 5.95 | 2.71 | 0.00 | 21.00 | 6.98 |
| <i>VHAGE₁</i> | 8.04 | 5.36 | 0.08 | 45.40 | - |
| <i>VHAGE₂</i> | 9.00 | 6.32 | 0.00 | 57.20 | - |
| <i>ATMIN</i> | 22.5 | 23.9 | 2.00 | 725.0 | - |
| <i>HHSIZ</i> | 2.35 | 1.17 | 1.00 | 10.00 | 2.3 |
| <i>EMPL</i> | 0.13 | 0.51 | -0.87 | 1.17 | - |
| <i>AGE</i> | 52.86 | 15.67 | 18.00 | 99.00 | 39.8 |
| <i>MINCUC</i> | 1736.75 | 1052.56 | 89.00 | 15000.00 | 1704 |
| <i>NBVEH</i> | 1.52 | 0.77 | 1.00 | 11.00 | 1.2 |
| <i>VEH2</i> | 0.40 | 0.49 | 0.00 | 1.00 | - |
| <i>HIGED</i> | 0.29 | 0.45 | 0.00 | 1.00 | 0.24 |
| <i>HIGSC</i> | 0.15 | 0.36 | 0.00 | 1.00 | 0.16 |
| <i>SECSC</i> | 0.36 | 0.48 | 0.00 | 1.00 | 0.30 |
| <i>PRISC</i> | 0.12 | 0.32 | 0.00 | 1.00 | 0.11 |
| <i>NOSC</i> | 0.09 | 0.28 | 0.00 | 1.00 | 0.19 |
| <i>URB</i> | 0.46 | 0.50 | 0.00 | 1.00 | 0.59 |
| <i>RUR</i> | 0.33 | 0.47 | 0.00 | 1.00 | 0.22 |
| <i>PAR</i> | 0.20 | 0.40 | 0.00 | 1.00 | 0.19 |
| Observations | 4630 | | | | |

average result for France in 2008. We see that the declared measure is in average higher than the odometer readings, however it is less variable. Moreover, the rank of the declared distance is lower than that of the odometer readings, which suggests that overall, individuals tend to underestimate the traveled distance. In average, the trip during the references week had a duration of 22 minutes.

We see that prices do not vary significantly among the households. This is because the survey was held during a year, period in which price variation are not very pronounced.

Around 40% of all vehicles use Diesel. The average fuel consumption of the main vehicle is 6.7 liters of fuel per 100 km, whereas the second vehicle consumes in average 6 liters per 100km. Households have kept their vehicle between 8 and 9 years.

Figure 2: Income distribution by geographic zone

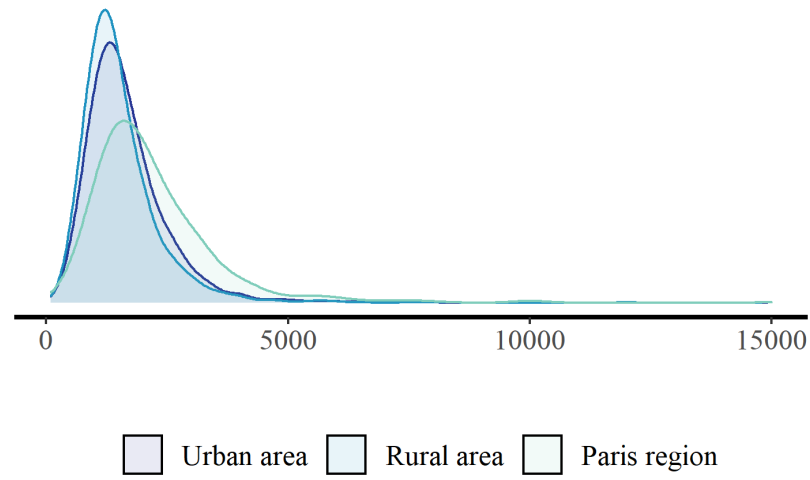
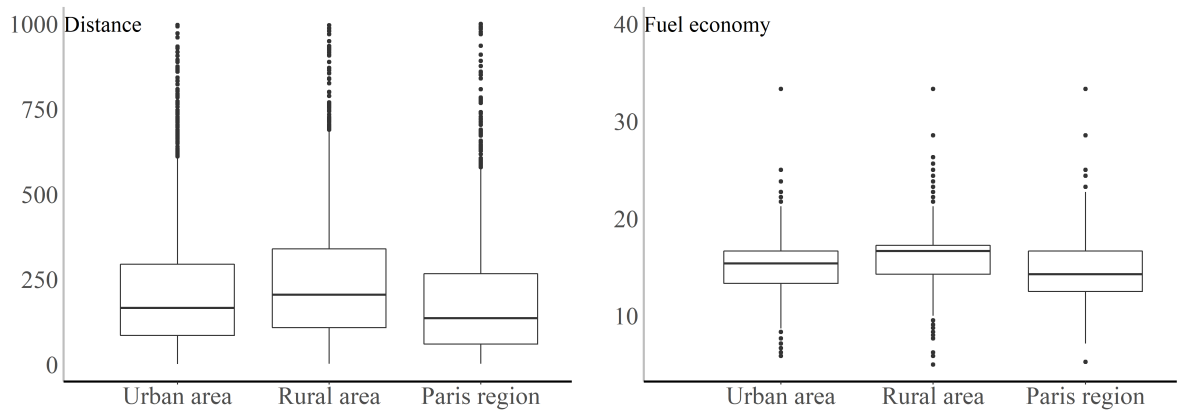


Figure 3: Weekly distance and fuel economy by geographic zone



(a) Weekly distance

(b) Fuel economy

Note: Extreme values were excluded.

Reading note: This figure presents the distribution of the weekly distance and the fuel economy by three geographic zones: Urban, Rural and Paris. We see that, in average, urban dwellers have a slightly more intensive use of the vehicle and have more efficient vehicles.

Heterogeneous use of vehicles

Towards the end of the year 2018, a social movement have taken the streets of the main french cities. This movement, known as the yellow jackets, emerged as an opposition force against fuel taxes increase, planned to start on January 1st 2019. Supporters of the movement argue that this measure will hurt more people in rural areas who rely more on vehicles for work and transportation compared with wealthier city dwellers who rely more on public transportation. In this section, we analyze this claim within our sample.

Figure 2 presents the (monthly) income distribution by geographic zone. The income has been adjusted by the number of consumption units in the household. It shows that households in the Paris region have the highest incomes. Over all, rural households have the lowest incomes and the lowest dispersion.

Figure 3 illustrates the driving distance and fuel economy per geographic area. This seems to support the idea that households living in rural areas tend to use more their vehicle compared to those living in urban areas, specially in the Paris region. Furthermore, they also tend to have more efficient vehicles, which indicates a potential rebound effect. Then, we can infer that rural households have more efficient vehicles, drive more often and have lower incomes.

These data seems to support the existence of heterogeneity in the fuel economy determined by the level of income and the geographic area. This heterogeneity can be a determinant factor in the demand for driving. Hence, our specifications allow for an heterogeneous effect of fuel economy on demand, first by including interactions with the geographic zone, and second, by testing the existence of non-linear effects in this relationship.

5 Estimation Results

In this section we present the output of the seven models presented in section 3. The results are presented in four parts.

First, we present the results from the three most basic specifications, comparing the two

measures of distance (odometer and declared) and the instrumentation of fuel economy. Second, we present the results from two specifications that introduce heterogeneous rebound effects. We test the significance of a quadratic effect and interactions with the geographic zone. Third, we present the results from a new methodology that corrects the sample selection bias. Finally, we conclude this section by comparing the rebound estimates of all seven specifications.

We estimate all models in the software R, using the package `systemfit` and the options 3SLS or OLS accordingly (Henningsen, Hamann, et al., 2007).

5.1 Odometer vs. Declared distance

Table 4 presents three estimates for distance: M1, M2 and M3. Standard errors are reported in parenthesis. Model M1 estimates vehicle-kilometers traveled (distance), from the odometer readings, as presented in equation (5) by using OLS.

Model M2 also estimates the distance measured with the odometer readings. In this model, distance and fuel economy of all the vehicles in the household (E_{ij}) are considered as the endogenous variables. It corresponds to the estimation of the system of equations formed by equations (5) and (7), by using 3SLS. Only the first equation is reported in this table. The equations for the fuel economy are presented in appendix D. Finally, M3 replicates M2 by using a declared measure of distance.

The coefficients for fuel economy of all vehicles in the household have a statistically significant effect on the distance in all three models. Models M1 and M2 have the expected sign for fuel economy (1) (of the first vehicle). On the contrary, model M3 exhibits a negative sign. As explained in the previous section, the declared distance, being only an approximation of the real traveled distance, suffers from a heaping bias. It seems that in this case households might have under-declared their driving distance. Furthermore, the greater variability in this variable decreases the goodness-of-fit in the model. As we can see, the independent variables in the model explain a lower proportion of the variance in the dependent variable (Adjusted R^2).

Table 4: Model for vehicle-kilometers traveled, odometer vs. declared distance

| | <i>Vehicle-Kilometers traveled</i> | | |
|------------------------|------------------------------------|-----------------------------|-----------------------------|
| | M1 | M2 | M3 |
| <i>FE</i> ₁ | 0.15 (0.05) ^{***} | 0.13 (0.06) ^{**} | -0.52 (0.10) ^{***} |
| <i>FE</i> ₂ | -0.05 (0.01) ^{***} | -0.06 (0.01) ^{***} | -0.08 (0.01) ^{***} |
| <i>PRI</i> | -1.08 (0.17) ^{***} | -1.03 (0.20) ^{***} | -2.09 (0.15) ^{***} |
| <i>DNBUS</i> | 0.12 (0.01) ^{***} | 0.12 (0.01) ^{***} | 0.03 (0.01) ^{***} |
| <i>DNTRA</i> | 0.03 (0.01) ^{**} | 0.03 (0.01) ^{**} | 0.01 (0.01) |
| <i>ATMIN</i> | 0.88 (0.02) ^{***} | 0.88 (0.02) ^{***} | 0.22 (0.02) ^{***} |
| <i>MINC</i> | 0.14 (0.03) ^{***} | 0.15 (0.03) ^{***} | 0.19 (0.03) ^{***} |
| <i>AGE</i> | -0.59 (0.05) ^{***} | -0.59 (0.05) ^{***} | -0.42 (0.05) ^{***} |
| <i>EMPL</i> | -0.14 (0.03) ^{***} | -0.14 (0.03) ^{***} | -0.11 (0.03) ^{***} |
| <i>HIGSC</i> | -0.01 (0.04) | -0.01 (0.04) | -0.04 (0.04) |
| <i>SECSC</i> | -0.06 (0.03) [*] | -0.06 (0.03) [*] | -0.10 (0.03) ^{***} |
| <i>PRISC</i> | -0.21 (0.05) ^{***} | -0.21 (0.05) ^{***} | -0.24 (0.04) ^{***} |
| <i>NOSC</i> | -0.24 (0.05) ^{***} | -0.23 (0.05) ^{***} | -0.27 (0.05) ^{***} |
| <i>TYP2</i> | -0.00 (0.03) | -0.01 (0.03) | -0.00 (0.03) |
| <i>TYP3</i> | -0.25 (0.05) ^{***} | -0.25 (0.05) ^{***} | -0.03 (0.04) |
| <i>TYP4</i> | -0.13 (0.06) ^{**} | -0.14 (0.06) ^{**} | 0.00 (0.05) |
| <i>TYP5</i> | -0.20 (0.07) ^{***} | -0.20 (0.07) ^{***} | -0.12 (0.07) [*] |
| <i>RUR</i> | 0.05 (0.03) | 0.05 (0.03) | 0.08 (0.03) ^{***} |
| <i>PAR</i> | -0.37 (0.04) ^{***} | -0.38 (0.04) ^{***} | -0.21 (0.03) ^{***} |
| <i>OUT</i> | 0.09 (0.11) | 0.09 (0.11) | -0.04 (0.10) |
| <i>FIRM</i> | 0.16 (0.14) | 0.15 (0.14) | 0.45 (0.13) ^{***} |
| <i>OTH</i> | 0.03 (0.15) | 0.04 (0.15) | 0.23 (0.14) [*] |
| Intercept | 2.52 (0.36) ^{***} | 2.34 (0.49) ^{***} | 4.78 (0.33) ^{***} |
| Adj. R ² | 0.38 | 0.38 | 0.19 |
| Observations | 4628 | 4628 | 4628 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

All variables are in logarithms, unless otherwise specified.

M1: Odometer readings, OLS. M2: Odometer readings, 3SLS.

M3: Declared distance, OLS.

The fuel economy (2) (of the second vehicle), have a negative sign. For models M1 and M2, this sign is opposite to that of fuel economy (1). This implies that the vehicle's own distance would decrease if other vehicles' fuel economy increases, indicating substitution effects among household vehicles. Models M1 and M2 support the existence of a rebound effect. Whereas M3 supports the idea of conservation (More in section 5.4).

The effect of current fuel prices is high and statistically significant, contrary to expected. The impact and significance of the exogenous variables X_j is very similar in all three models. These models suggest that distance traveled increases with the distance from the household to urban public transports (bus, subway, tram). This is consistent with literature findings (e.g. Gillingham, 2018) suggesting that, in Europe, public transports are realistic substitutes to the use of private vehicle.

The main coefficient for income is positive and statistically significant. Literature suggests that income have a non linear effect in the demand for driving. Meaning that after a given level of income, the rebound effects decreases (e.g. Hymel et al., 2010; Small and Van Dender, 2007). In the next section, we test a quadratic effect of income in the demand for driving.

Distance traveled is significantly higher for individuals having a higher education level. The geographic variables have a significant effect on driving, which may reflect the effect of congestion. In general, the distance is lower in highly urbanized and dynamic areas (Paris). This result is consistent with previous findings such as Small and Van Dender (2007).

5.2 Household heterogeneity

Table 5 (Page 73) presents two new estimates for the distance: M4 and M5. Standard error are reported in parenthesis. The variable distance in these models is measured with the odometer readings and the estimation technique is 3SLS.

Model M4 extends model M1 by including quadratic effects for fuel economy, income and age of the household reference individual. It corresponds to the estimation of the

Table 5: Model for vehicle-kilometers traveled, household heterogeneity

| | <i>Vehicle-Kilometers traveled</i> | |
|---------------------|------------------------------------|------------------|
| | M4 | M5 |
| FE_1 | 6.44 (1.79)*** | 0.17 (0.06)*** |
| FE_1^2 | -1.09 (0.31)*** | |
| $FE_1 \times RUR$ | | 0.00 (0.02) |
| $FE_1 \times PAR$ | | -0.15 (0.02)*** |
| FE_2 | 0.75 (0.46) | -0.07 (0.02)*** |
| FE_2^2 | -0.28 (0.16)* | |
| $FE_2 \times RUR$ | | 0.03 (0.02) |
| $FE_2 \times PAR$ | | 0.06 (0.03)** |
| PRI | -0.92 (0.18)*** | -0.91 (0.17)*** |
| $DNBUS$ | 0.12 (0.01)*** | 0.11 (0.01)*** |
| $DNTRA$ | 0.03 (0.01)** | 0.03 (0.01)*** |
| $ATMIN$ | 0.88 (0.02)*** | 0.88 (0.02)*** |
| OPT | 0.19 (0.03)*** | 0.20 (0.03)*** |
| $MINC$ | 1.27 (0.42)*** | 1.26 (0.39)*** |
| $MINC^2$ | -0.08 (0.03)*** | -0.07 (0.02)*** |
| AGE | 5.80 (0.91)*** | 6.41 (0.88)*** |
| AGE^2 | -0.85 (0.12)*** | -0.93 (0.12)*** |
| $EMPL$ | -0.04 (0.04) | -0.02 (0.04) |
| $HIGSC$ | 0.01 (0.04) | 0.00 (0.04) |
| $SECSC$ | -0.05 (0.04) | -0.07 (0.03)** |
| $PRISC$ | -0.14 (0.05)*** | -0.15 (0.05)*** |
| $NOSC$ | -0.18 (0.05)*** | -0.18 (0.05)*** |
| $TYP2$ | -0.03 (0.03) | -0.02 (0.03) |
| $TYP3$ | -0.25 (0.05)*** | -0.25 (0.05)*** |
| $TYP4$ | -0.11 (0.06)* | -0.15 (0.06)** |
| $TYP5$ | -0.24 (0.07)*** | -0.22 (0.07)*** |
| RUR | 0.05 (0.03) | |
| PAR | -0.39 (0.04)*** | |
| OUT | 0.19 (0.11)* | 0.20 (0.11)* |
| $FIRM$ | 0.12 (0.14) | 0.14 (0.14) |
| OTH | 0.03 (0.15) | 0.04 (0.15) |
| Intercept | -22.66 (3.21)*** | -14.93 (2.24)*** |
| Adj. R ² | 0.36 | 0.40 |
| Observations | 4628 | 4628 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

All variables are in logarithms, unless otherwise specified.

M4: Quadratic effects, 3SLS. M5: Fuel economy by zone, 3SLS.

system formed by equations (5) and (7)⁶ with 3SLS. Only the estimation output for the first equation is reported in this table. The estimation output for the equation E_{ij} is presented in appendix D. Model M5 corresponds to the estimation of the system formed by equations (6) and (7)⁷ with 3SLS.

The coefficients for the fuel economy of all vehicles in the household have a statistically significant effect on the distance. Model M4 support the hypothesis of a non-linear relationship between fuel economy and driving distance. Model M5, on the other hand, suggests that the rebound effect differs among geographic zones. The interaction term between geographic zone and fuel economy (1) is negative and statistically significant for the Paris region, suggesting a lower rebound (More in section 5.4).

The effect of current fuel prices on driving distance is still significant, although a little lower than the previous models. The impact of the other explanatory variables (X'_j) is very similar to the previous models. We have a new variable including some vehicle attributes, which is highly significant and has a positive impact in the demand for driving. Which provides further evidence that driving demand is correlated with the vehicles attributes.

Furthermore, these models suggest the existence of quadratic effects of income and age on the demand for driving. Families with lower income tend to increase their driving distance as they get wealthier, once they have reach an income between 2 870 and 2 983€ per month, they decrease the amount of driving. Recall that income is adjusted to the household composition⁸, meaning that it represents their living standard. According to the Insee (2010), this income corresponded to the 7th income decile in 2008. Similarly, younger households tend to drive more as the get older. When they reach 30 years old, they decrease their driving demand.

Table 6: Model for vehicle-kilometers travels, sample selection bias correction

| <i>Households having :</i> | <i>Vehicle-Kilometers traveled</i> | | | |
|----------------------------|------------------------------------|--------------------|------------------|--------------------|
| | <i>M6</i> | | <i>M7</i> | |
| | <i>1 vehicle</i> | <i>More than 1</i> | <i>1 vehicle</i> | <i>More than 1</i> |
| FE_1 | 0.04 (0.53) | 8.85 (2.12)*** | 0.08 (0.07) | 0.46 (0.16)*** |
| FE_1^2 | -0.00 (0.09) | -1.53 (0.37)*** | | |
| $FE_1 \times RUR$ | | | 0.01 (0.01) | 0.02 (0.06) |
| $FE_1 \times PAR$ | | | -0.16 (0.02)*** | -0.29 (0.07)*** |
| FE_2 | | -0.20 (0.25) | | -0.07 (0.04) |
| FE_2^2 | | 0.07 (0.09) | | |
| $FE_2 \times RUR$ | | | | 0.02 (0.07) |
| $FE_2 \times PAR$ | | | | 0.18 (0.08)** |
| PRI | -0.91 (0.22)*** | -1.15 (0.29)*** | -0.90 (0.22)*** | -0.79 (0.30)*** |
| $DNBUS$ | 0.15 (0.01)*** | 0.06 (0.03)** | 0.15 (0.01)*** | 0.08 (0.03)*** |
| $DNTRA$ | 0.05 (0.02)*** | 0.03 (0.02) | 0.05 (0.02)*** | 0.04 (0.02)* |
| $ATMIN$ | 0.95 (0.03)*** | 0.80 (0.03)*** | 0.94 (0.03)*** | 0.76 (0.03)*** |
| OPT | 0.15 (0.04)*** | 0.22 (0.05)*** | 0.15 (0.04)*** | 0.22 (0.04)*** |
| $MINC$ | 1.68 (0.50)*** | 1.46 (0.86)* | 1.68 (0.50)*** | 2.03 (0.80)** |
| $MINC^2$ | -0.10 (0.03)*** | -0.08 (0.05) | -0.10 (0.03)*** | -0.11 (0.05)** |
| AGE | 5.07 (1.04)*** | 4.85 (1.83)*** | 5.08 (1.04)*** | 5.71 (1.73)*** |
| AGE^2 | -0.76 (0.14)*** | -0.70 (0.24)*** | -0.76 (0.14)*** | -0.80 (0.23)*** |
| $EMPL$ | -0.12 (0.05)** | -0.22 (0.08)*** | -0.12 (0.05)** | -0.24 (0.08)*** |
| $HIGSC$ | 0.05 (0.05) | -0.05 (0.06) | 0.05 (0.05) | -0.03 (0.06) |
| $SECSC$ | -0.05 (0.04) | -0.07 (0.06) | -0.05 (0.04) | -0.06 (0.05) |
| $PRISC$ | -0.14 (0.06)** | -0.21 (0.09)** | -0.13 (0.06)** | -0.20 (0.08)** |
| $NOSC$ | -0.19 (0.06)*** | -0.20 (0.09)** | -0.19 (0.06)*** | -0.17 (0.09)* |
| $TYP2$ | 0.03 (0.05) | -0.12 (0.05)** | 0.03 (0.05) | -0.11 (0.05)** |
| $TYP3$ | -0.30 (0.06)*** | -0.46 (0.10)*** | -0.30 (0.06)*** | -0.47 (0.10)*** |
| $TYP4$ | -0.16 (0.07)** | -0.26 (0.14)* | -0.16 (0.07)** | -0.31 (0.13)** |
| $TYP5$ | -0.21 (0.08)** | -0.40 (0.14)*** | -0.22 (0.08)** | -0.38 (0.14)*** |
| RUR | 0.02 (0.04) | 0.09 (0.05)* | | |
| PAR | -0.47 (0.04)*** | -0.38 (0.07)*** | | |
| OUT | 0.16 (0.12) | 0.14 (0.25) | 0.16 (0.12) | 0.18 (0.24) |
| $FIRM$ | 0.23 (0.18) | 0.00 (0.22) | 0.24 (0.18) | -0.02 (0.22) |
| OTH | 0.14 (0.22) | 0.03 (0.21) | 0.13 (0.22) | -0.03 (0.20) |
| Inverse Mills ratio | 0.16 (0.03)*** | 0.24 (0.08)*** | 0.16 (0.03)*** | 0.29 (0.07)*** |
| Intercept | -14.79 (2.79)*** | -25.30 (5.05)*** | -14.94 (2.71)*** | -18.18 (4.52)*** |
| Adj. R^2 | 0.43 | 0.29 | 0.43 | 0.34 |
| Observations | 2777 | 1851 | 2777 | 1851 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. All variables are in logarithms, unless otherwise specified.

M6: Sample selection correction, no interactions. M7: Sample selection correction, interactions.

5.3 Sample selection bias correction

Table 6 (Page 75) presents two new estimates for driving distance: M6 and M7. Standard errors are reported in parenthesis. These models address the sample selection bias due to the fact that households have different number of vehicles. Following the method explained in section 3.5, each model is estimated for two sub-samples: households having only one vehicle and households having more than one vehicle. Model M6 includes non-linear effects and model M7 includes geographic heterogeneity. The models for the sub-samples of households having one vehicle were estimated using OLS, the models for the other sub-sample were estimated using 3SLS (See appendix C).

We see that the coefficient for fuel economy is not statistically significant for the sub-sample having only one vehicle in any model. These households will react more to changes in prices. In the sub-sample having more than one vehicle, the coefficient for fuel economy of the second vehicle is not significant for model M6.

These models support the existence of a rebound effect only among households having more than one vehicle. The rebound effect will depend on the level of fuel economy (M6) and the geographic region (M7). The interactions terms between geographic zone and fuel economy (1) are statistically significant for Paris. It suggests that the rebound effect in urban areas (reference) is similar to that in rural areas and significantly higher than in Paris.

The effect of current fuel prices on driving distance is similar to what we observed in previous sections. The impact of the other explanatory variables X'_j is very similar to the previous models.

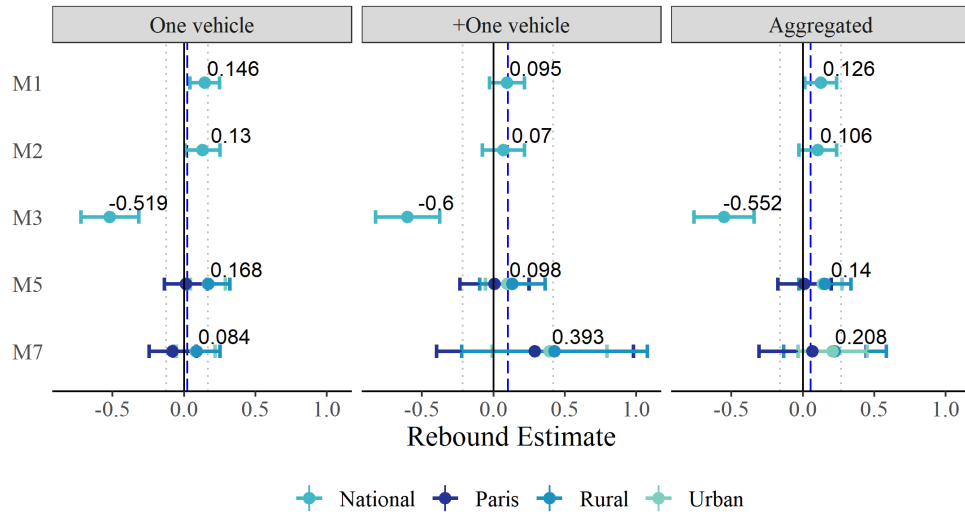
Both models M6 and M7 suggests a quadratic effect of income and age in driving distance. The results suggest that the demand for driving reach an inflection point with incomes between 4 200€ and 5 400€ per month. According to Insee (2010), this income corresponds to the top two income decile in 2008. Households tend to drive more as the

⁶This equation is modified by including quadratic terms of the instruments.

⁷This equation is modified by including interactions of the instruments.

⁸Total income is divided by average number of consumption units in the household.

Figure 4: Estimates of the rebound effect by number of vehicles and zone



Reading note: Estimated rebound effect per geographic zone and its 95% confidence interval. The labels present the rebound at a national level for model M1-M3 and urban level for models M5 and M7.

get older. When they reach 28 to 34 years old, they decrease their driving demand.

The coefficient for the inverse Mills ratio is significant, supporting the existence of a sample selection bias.

5.4 Comparison of the rebound effect estimates

In this section, we present and compare the rebound effect estimations from the seven models presented previously. Figure 4 synthesizes the estimates of the rebound effect for models M1-M3, M5 and M7. It presents the rebound estimates for households having one vehicle, several vehicles and the aggregated rebound. The dotted lines represent the average of all estimations and their respective lower and upper bounds of the 95% confidence interval. The labels present the rebound at a national level when there are no interactions and urban level, when there are interactions. We presented the test of validity of instruments in appendix C.

The estimates of the rebound effect are sensitive to the method used. Model M3 is the only one suggesting conservation of fuel, meaning that an increase in fuel economy will

lead household to reduce their demand for driving. As we explained before, this model may be problematic due to an approximation bias in the dependent variable. The other 4 models predict a rebound effect over all, although significantly lower for the Paris region. The magnitude of the rebound is lower to what the literature predicts.

The estimated rebound predicted with model M1 is 12.6%. This model was with estimated with OLS, which in the presence of endogeneity may over estimate the effect⁹. When the endogeneity of fuel efficiency is taken into account, in model M2, the rebound effect goes down to 10.6%. According to these models, in the medium-run between 10.3% and 12.6% of the gains from fuel efficiency improvements would be lost due to demand increase.

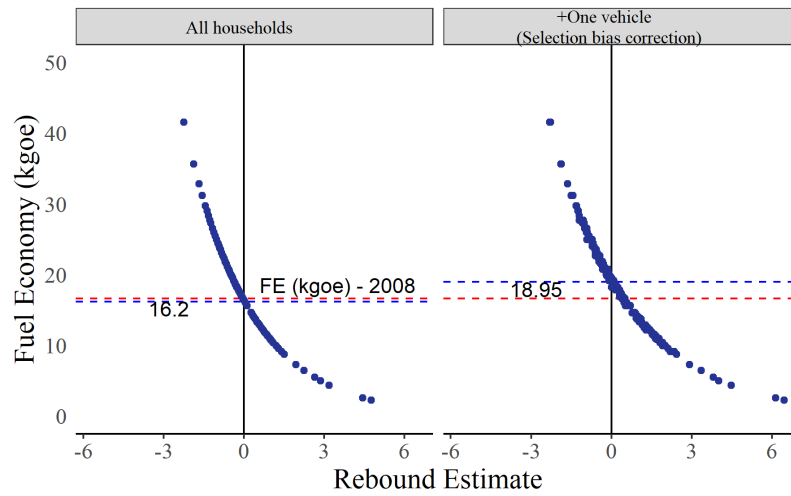
Take for instance a single-vehicle household, having a vehicle that can be driven 19 km for every liter of fuel *kgeo* (or equivalently, a vehicle consuming 5,3 liters of fuel *kgeo* per 100 km) and usually driving 236 km per week. Assume this household acquire a costless new vehicle with a 10% improvement in fuel economy, all other things equal. Meaning that this new vehicle can be driven 21 km for every liter of fuel *kgeo* (or equivalently, a vehicle consuming 4,8 liters of fuel *kgeo* per 100 km). According to models M1 and M3, the driving distance would increase between 0.103 and 0.126% per every 1% improvement in efficiency, that is an increase of 2.4 and 3 km per week.

Furthermore, model M5 and M7 introduce heterogeneous rebound effects and greater heterogeneity among households. Models M7 enhance model M5 by addressing the sample selection bias. The coefficient of the inverse Mills ratio is significant, thus indicating the existence of a selection bias that needs to be corrected. These models predict a close to zero rebound in the Paris region (in one case (one vehicle, M7) there is no rebound) and the confidence interval always include zero (no statistically significant). For the other areas, the rebound is very close, its magnitude is estimated between 14% and 20%. The confidence interval for the urban area is mostly on the right side of zero.

Model 7, predicts a rebound effect close to 40% for households having more than one

⁹The endogeneity test performed on model M1 fail to reject the null hypothesis of exogenous fuel economy. However, in other model specifications the test was in favor of endogeneity, therefore we decided to take into account a possible endogeneity issue in model M2 (See appendix C).

Figure 5: Estimates of the quadratic rebound effect



Reading note: The blue line represents the efficiency level at the inflection point. The red line represents the average level of efficiency (in *kgoe*) in France in 2008. Extreme values were excluded.

vehicle, contrary to model M5 that predicts only 10%. In the case of households have only one vehicle, M5 over estimates the rebound effect. This difference is explained by the sample selection correction. Model M5 estimates over the whole sample, whereas model M7 estimates on a sub-sample of households, depending on the number of vehicles.

If we take again the single-vehicle household, now say they live in a urban area, having a vehicle that can be driven 19 km for every liter of fuel *kgoe* (or equivalently, a vehicle consuming 5,3 liters of fuel *kgoe* per 100 km) and usually driving 236 km per week. Assume they benefit from a 10% improvement in fuel economy, all other things equal. According to model M5, the driving distance would increase between 0.14% and 0.208%, that is an increase between 3.3 and 5 km per week.

Figure 5 presents the rebound estimates for model M4 and M6. The blue line represents the level of efficiency (in *kgoe*) at which the sing of the rebound changes. The red line represents the average level of efficiency (in *kgoe*) in France in 2008.

These models include a quadratic coefficient for fuel economy, in order to control for the existence of a non-linear rebound. Model M6 enhance model M4 by addressing the sample selection bias. Once again, the coefficient of the inverse Mills ratio is significant.

Model M4 predicts a positive rebound when fuel economy (in *kgoe*) is lower than 16.2 km per liter of fuel (or equivalently, fuel consumption greater than 6.17 liters of fuel per 100 km), corresponding to an average rebound of 40.8%. In our sample, 34% of households falls into this category.

Model M6, predicts no rebound effect for households having only one vehicle (around 60% in this sample). As for households having more than one vehicle, the model predicts a positive rebound when fuel economy is lower than 19 km per liter of fuel (or equivalently, fuel consumption greater than 5.3 liters of fuel per 100 km), corresponding to an average rebound of 65%. In our sample, 13% of households are found in this category.

For comparison, in France in 2008, the average fuel economy was around 14.3 km per liter of fuel. This is equivalent to about 16.6 km per liter of fuel in *kgoe* or 6 liter of fuel per 100 km (See appendix A). In 2018, average fuel consumption was around 15.8 km per liter of fuel, which is equivalent to 19.5 km per liter of fuel (or equivalently, fuel consumption of 5.12 liters of fuel per 100 km).

Overall, the estimated magnitudes of the rebound effect seem relatively consistent with global estimates going from 20% to 40% (Gillingham et al., 2016) and, to a certain extent, to estimates with European data which tend to be higher.

6 Policy simulation: a smart kilometer tax

In this section we simulate a dynamic tax scheme and discuss its implications on travel behavior. Likewise, we assess the tax rate needed to reduce the amount of kilometers traveled and the rebound effect.

We focus on the impact of a smart kilometer tax. This policy has been implemented in Belgium for heavy goods vehicles (HGV) of over 3.5 tons and since 2020 is being tested for passenger cars. The policy introduces a charge proportional on distance covered. The tax is differentiated according to several factors including the vehicle level of emissions, the type of route, the vehicle weight and the region. Currently there is a debate into different

Table 7: Kilometer tax rate, High scenario

| Hour | Euro Standard | Urban | Rural | Paris |
|---------|---------------|-------|-------|-------|
| No peak | Euro 1-4 | 0.083 | 0.076 | 0.09 |
| No peak | Euro 5 | 0.07 | 0.05 | 0.09 |
| Peak | Euro 1-4 | 0.119 | 0.102 | 0.135 |
| Peak | Euro 5 | 0.105 | 0.076 | 0.135 |

Reading Note: The Euro Standards define the limit of emission of new vehicle sold in the EU. The first generation for passenger cars, Euro 1, came into effect in 1992. Euro 2 began in January 1996, Euro 3 in January 2000 and Euro 4 in January 2005. Since then, two new generations, with several versions each, have been applied, we are currently in Euro 6.

Belgian regions to enlarge the kilometer tax to the entire fleet, including passenger cars (Renson, 2018).

We created a baseline scenario representing the situation in 2008. This scenario was computed by taking into account the share of taxes in the fuel price that year. For Diesel cars, taxes made up 59% of the fuel price and for petrol cars, it was 66% (Sénécat, 2018).

Furthermore, we create a tax scheme based in the Euro Standard of the vehicle and the urban unit, where the kilometer rate is lower for vehicles following more recent Euro Standards, for trips made outside areas of high congestion and outside peak hours. We consider a high scenario and a low scenario. Furthermore, the taxes under the latter are close to the tax scheme observed in 2008. Table 7 presents the tax scheme under the high scenario. Taxes under the low scenario are half those of the high scenario.

Moreover, we add a flat fee of 0.1c€ to the kilometer tax rate presented in Table 7 if the household is within 1 km of a public transport facility.

Notice that our model does not estimate the price elasticity. The coefficient for price estimated in our model cannot be interpreted as a price elasticity because it does not include variations in prices between several years (Sorrell, 2012). Thus, in order to compute the simulation, we use the price elasticity estimated in the literature (e.g. Delsaut, 2014; Graham and Glaister, 2002) which is -0.29.

Table 8 presents the average tax rate and fuel expenses by urban unit for real fuel prices

Table 8: Average tax rate and fuel expenses by geographic zone

| | <i>Urban area</i> | | <i>Rural area</i> | | <i>Paris region</i> | |
|---|-------------------|-------|-------------------|-------|---------------------|-------|
| | mean | SD | mean | SD | mean | SD |
| Average tax rate per 1 km | | | | | | |
| Baseline | 0.05 | 0.02 | 0.05 | 0.01 | 0.06 | 0.03 |
| Simulation - low | 0.05 | 0.01 | 0.04 | 0.01 | 0.05 | 0.01 |
| Simulation - high | 0.09 | 0.01 | 0.08 | 0.01 | 0.11 | 0.01 |
| Average individual expenses in fuel (reference week) | | | | | | |
| Baseline | 19.03 | 20.14 | 20.94 | 18.36 | 18.73 | 23.10 |
| Simulation - low | 18.19 | 17.20 | 18.72 | 16.09 | 18.65 | 21.45 |
| Simulation - high | 29.02 | 26.98 | 29.23 | 25.09 | 30.20 | 34.42 |
| Observations | 2141 | | 1548 | | 941 | |

in 2007-2008 (baseline scenario) and the two simulation scenarios.

Under the baseline scenario, the average tax rate is similar for all urban areas, including Paris. On the other hand, the simulated scenarios penalize drivers in urban areas, specially those in the Paris region, which can potentially contribute to reduce congestion.

Even though the low scenario also penalizes congestion, the tax rates per kilometer are closer to the baseline. Under the high scenario, rates double those of the low and baseline scenarios. What we see is that both the baseline and low scenario fail to correct potential congestion effects.

Under the higher tax scheme, the current (during the reference week) fuel consumption of household located in Paris would lead to higher expenses due to the congestion penalization. In second place, rural households would expend more mainly because they tend to drive more (Figure 3).

Finally, Table 9 gives insight about the tax rate required to neutralize the rebound effect, all other things remaining constant. In other words, the tax rate required to prevent distance from increasing after an improvement in fuel efficiency.

Moving from the baseline situation to the low tax scheme, the price per liter of fuel increases 4% in Paris while decreasing around 2% in other urban areas and 10% in rural areas. In this case driving distance would decrease only in Paris by 1%, whereas it would

Table 9: Variation in distance traveled and fuel prices compared to baseline scenario

| | Scenario | <i>Urban area</i> | | <i>Rural area</i> | | <i>Paris region</i> | |
|---|----------|-------------------|------|-------------------|------|---------------------|------|
| | | mean | SD | mean | SD | mean | SD |
| Fuel price elasticity | | -0.29 | | -0.29 | | -0.29 | |
| $\Delta\%$ Price per fuel liter | Low | -0.02 | 0.19 | -0.09 | 0.18 | 0.04 | 0.22 |
| $\Delta\%$ Price per fuel liter | High | 0.58 | 0.36 | 0.43 | 0.35 | 0.68 | 0.42 |
| Supplementary decrease in traveled distance | | | | | | | |
| $\Delta\%$ | Low | 0.01 | 0.05 | 0.03 | 0.05 | -0.01 | 0.06 |
| $\Delta\%$ | High | -0.17 | 0.10 | -0.12 | 0.10 | -0.20 | 0.12 |
| Observations | | 2141 | | 1548 | | 941 | |

increase by 1% in other rural areas and 3% in rural areas. In other words, this tax scheme does not help in neutralizing the rebound effect.

Moving from the baseline to the high tax scheme, prices per fuel liter increase between 43% and 68%, depending on the geographic zone, the Paris region having the higher tax rate, followed by other urban areas and rural areas. The distance would decrease between 12% and 20%. This scenario helps in reducing the rebound effect in all of the cases presented in the previous section.

In 2018, the overall price for petrol increased 4.8% with respect to 2008 prices (constant), for diesel the increase was 15.7%. However, most of the increase is explained by higher oil prices (including distribution and refining), taxes accounts for 44% of the increase in diesel prices. As for petrol prices, taxes actually decreased during the period.

This simulation exercise suggests that tax schemes can be complementary to fuel efficiency measures and that they can be tailored as to take into account individuals mobility patterns as well as social and financial conditions. Taking into account households heterogeneity, a significant increase in taxes is needed to effectively counter the rebound effect. Therefore, additional measures, improving the access to public transportation or car sharing for instance, should be considered in order to reduce taxes regressive effects on those who depend on the private car while keeping the rebound effect at a minimum level.

7 Conclusion

In this chapter, we estimate the rebound effect for private transportation using micro-level data in France for 2007-2008. We use the primary definition of the direct rebound effect, which is the consumers' reaction to a change in energy efficiency. We estimate seven specifications for distance traveled. We instrument the fuel efficiency with the vehicle's emissions deviation from the European emissions standards current in 2008, the fiscal horsepower and the past fuel prices. We allow separate coefficients for fuel efficiency and fuel prices. We include potential substitutes for driving by taking into account the existence of several vehicles in the household and the availability of public transportation. Furthermore, we correct for the sample selection bias that arise due to the different number of vehicles available for each household.

This empirical work suggests the existence of a rebound effect at the national level and in urban and rural areas outside Paris. The estimates suggest that, in the medium-run, about between 15% and 18% of gains from fuel efficiency improvements are lost due to an increase in the demand for driving, known as the direct rebound effect. This magnitude seems relatively lower than global estimates going from 20% to 40%.

We found that the rebound effect is sensitive to household heterogeneity. There is a conservation effect (negative rebound) in Paris. Furthermore, our models predict a positive overall rebound effect when fuel economy is lower than 16.2 km per liter of fuel (or equivalently, fuel consumption greater than 6.17 liters of fuel per 100 km). As for households having more than one vehicle, the model predicts a positive rebound when fuel economy is lower than 19 km per liter of fuel (or equivalently, fuel consumption greater than 5.3 liters of fuel per 100 km).

In France in 2008, the average fuel economy was around 14.3 km per liter of fuel. This is equivalent to about 16.6 km per liter of fuel in *kgoe* or 6 liter of fuel per 100 km. In 2018, average fuel consumption was around 15.8 km per liter of fuel, which is equivalent to 19.5 km per liter of fuel (or equivalently, fuel consumption of 5.12 liters of fuel per 100 km).

Moreover, the model supports the hypothesis of non-linear effect of income in driving distance, implying that families with lower income tend to increase their driving distance as they get wealthier, but once they have reach the 7th income decile (2008), 3 682€ per month, they decrease the amount of driving, and therefore the rebound decreases.

Likewise, we find that distance traveled increases with the distance from the household to urban public transports. This result suggests that, in Europe, public transports are realistic substitutes to the use of private vehicle. Other household characteristics such as education, number of vehicles and location regarding the urban centers have proved to be relevant to travel distance and fuel economy.

Our estimates provide further evidence into endogeneity of fuel economy as well as the interdependence of travel distance among vehicles in multi-vehicle households.

Finally, the simulation of a smart kilometer tax, with rates varying with fuel efficiency and urban unit, suggests that the rebound effect can be neutralized when tax rates twice as high as those in 2007/2008 levels.

In conclusion, it seems that differentiated taxes can be a solution to tackle rebound effects, congestion and regressive effects arising from the high taxes, such as the claims made by the recent social movements in France. Ultimately, differentiated taxes can be used as a complimentary measure to fuel efficiency improvement policies seeking to counter the rebound effect and achieve reduction in carbon emissions. However, additional measures, such as improving the access to public transportation or car sharing, should be considered in order to reduce taxes regressive effects while keeping the rebound effect at a minimum level.

The main message of this chapter is that we need to take into account the heterogeneity between the households to better account for the rebound effects.

The main limits concerning the data is that information on the secondary vehicle is very incomplete. For instance, over the 1853 households in the sample having more than one vehicle, there 232 observations missing in the variable of fuel efficiency of the secondary.

This may reduce the quality of the results.

A further extension of this work, would be to replicate this analysis on data for several years to check the temporal validity of these results.

Appendices

A Data cleaning and format

We did an extensive work of data clean and format. The raw data was presented in 19 different subsets of data. Each of these data subset included variables in a particular statistical unit (household or individual), a specific vehicle (for instance, private vehicle, motor cycle or bicycle) and the information from the card describing every trip made during the reference week. Overall, these subsets of data gather over 1500 variables.

After reviewing all the available variables, we decided which variables would need to be created from the data and which could be taken as is.

The survey includes a variable on the number of kilometers driven with the vehicles in the household over the last 12 months. However, this variable is declared and is not an accurate measure of the distance traveled. Usually, this variable suffers from a heaping bias, which arises because of the approximation.

We compute instead a measure of distance by using the information collected in the cards filled during the reference week. These cards include the number of kilometers driven extracted directly from odometers reading. Even if there is still room for error, this measure is much more accurate. The variable distance was computed by aggregating the number of kilometers driven during the week for every vehicle and household.

There was a significant amount of missing values in the distance variable. Some households only registered a few trips during the week. There is no way of knowing if they did not use the vehicle the other days or if it they did not report it. Therefore, to avoid misrepresentations of the weekly distance, we kept only the households with observations during the whole week.

These cards also contain very detailed information about trip characteristics, such as the duration, the number of individuals in the vehicle and the reason for the trip, among others. We use the time spent in every trip to compute the average trip duration per

household and vehicle. Other variables were computed but not included in the analysis because of lack of significance, abundance of missing values or multicollinearity. These include the sum of toll and parking fees, the share of commuting trips, leisure trips (e.g. holidays) or everyday trips, the number of trips made during the week, average speed per trip (by using the duration and the distance).

From the subset of data on the vehicle we extract the variables about the vehicle characteristics, namely, fuel consumption, vehicle age, horsepower, weight and annual declared distance.

Knowing that vehicles in the sample use different type of fuels, mainly gasoline and diesel, the energy efficiency measure cannot be directly compared. This is because the amount of energy produced by one unit of diesel is not equivalent to the amount of energy produced by one unit of gasoline. Therefore, following Kemel et al. (2011), we converted this measure of efficiency to a common unit, *Kilograms of oil equivalent* (kgoe), in order to make them comparable.

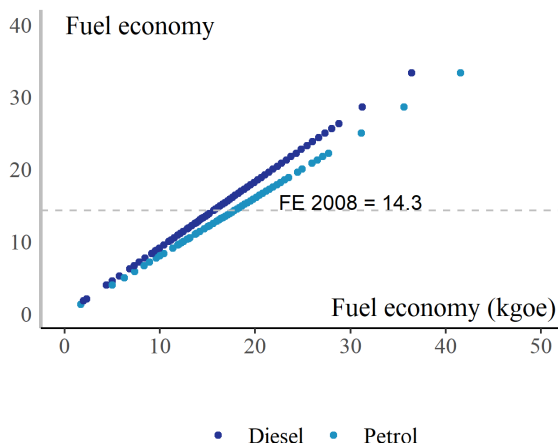
A kilogram(s) of oil equivalent, usually abbreviated as kgoe, is a normalized unit of energy. By convention it is equivalent to the approximate amount of energy that can be extracted from one kilogram of crude oil. It is a standardized unit, assigned a net calorific value of 41 868 kilojoules/kg and may be used to compare the energy from different sources (Eurostat, 2021).

A liter of petrol is equivalent to 33 572.2 kilojoules. A liter of diesel is equivalent to 38 290.4 kilojoules (U.S. Energy Information Administration). Take the example of a diesel vehicle that can be driven 16 km per every liter of fuel. The fuel economy of such vehicle in *kgoe* would be $16 \times \frac{38290.4}{41868} = 14.63 \text{ kgoe}$. If it is a petrol vehicle, it would be $16 \times \frac{33572.2}{41868} = 12.83 \text{ kgoe}$.

Figure 6 shows the equivalence between fuel economy and the converted fuel economy in (kgoe) by type of fuel.

Subsequently, from the other subsets of data, we chose a set household characteristics and

Figure 6: Equivalence fuel economy in kgoe



control variables that may affect driving distance. Some more variables were created, such as the number of driving licenses in the households, the dummy variable that indicates if the household have more than one vehicle and some variables regarding the year of the acquisition of the vehicle.

These data subsets were merged by using the household's unique identification number, present in all of them. The final sample is composed of 4630 observations.

Furthermore, the variable for the deviation from European emissions standards was computed as the difference between CO₂ emission standard in Europe for 2009, 130 *g/km*, and the amount of CO₂ emitted by the vehicle.

To compute the average CO₂ emission from fuel consumption, we multiply the amount of CO₂ per liter of fuel emitted due to combustion by the fuel consumption of the vehicle. We follow the score of GHG Emissions from a typical passenger vehicle computed by the United States Environmental Protection Agency (EPA). According to the EPA, the combustion of gasoline emits 8 887 grams CO₂/gallon. Which is about 2 350 grams CO₂/liter. The combustion of diesel emits 10 180 grams CO₂/gallon. Which is about 2 690 grams CO₂/liter.

Finally, we use the statistical series on monthly domestic fuel prices from the database Pégase. All prices were converted to constant prices of 2009. The current fuel price was computed by merging the data on prices with the main data base by the date (month/year)

of the survey. The past fuel prices were computed by merging the data on prices with the main data by the date (month/year) of the vehicle acquisition.

One of the main complications of the final data is that all the variables concerning the second vehicle on the household have missing entries for the all the household that have only one vehicle. Following the literature, all of these missing values were converted to zero. Notice that this is no longer problematic when we performed the model correcting for sample selection bias.

B Rebound estimates by model

The Table 11 summarize the estimated rebound effect for all model specifications. It is organized by geographic region and quadratic effect.

Table 10: Estimations for the rebound effect of models M1-M3

| | | <i>Rebound effects</i> | | |
|----|------------------------------------|------------------------|-----------------------|------------|
| | | One vehicle | More than one vehicle | Aggregated |
| M1 | National | 0.129 | 0.07 | 0.106 |
| M2 | National | 0.146 | 0.095 | 0.126 |
| M3 | National | -0.519 | -0.6 | -0.552 |
| M5 | Urban | 0.168 | 0.098 | 0.14 |
| | Rural | 0.17 | 0.007 | 0.156 |
| | Paris | 0.014 | 0.133 | -0.011 |
| M7 | Urban | <i>0.0843</i> | 0.393 | 0.207 |
| | Rural | <i>0.089</i> | 0.428 | 0.225 |
| | Paris | -0.079 | 0.29 | 0.068 |
| M4 | National | 0.108 | <i>-0.744</i> | -0.233 |
| | <i>Fuel economy inflection at:</i> | | 16.238 | |
| M6 | National | <i>0.028</i> | 0.167 | 0.096 |
| | <i>Fuel economy inflection at:</i> | | 18.995 | |

Italics: the rebound effect is not statistically different from zero.

Table 11: Estimations for the quadratic income and age effects

| | | <i>Quadratic effects</i> | | | |
|----|------|--------------------------|-------------------|-------------------|-------------------|
| | | Maximal income | | Maximal age | |
| M4 | | 2870 | | 29.84 | |
| M5 | | 2983 | | 31.2 | |
| | | <i>S-Sample 1</i> | <i>S-Sample 2</i> | <i>S-Sample 1</i> | <i>S-Sample 2</i> |
| M6 | 4257 | | 5391 | 28.1 | 32.4 |
| M7 | 4210 | | 4991 | 28.1 | 34.7 |

Income is weighted by the number of consumption units in the household.

C Specification tests

The rebound literature considers that fuel economy may be endogenous to driving distance. Therefore, we have two potentially endogenous variables in the modeling: E_{1j} and E_{2j} . Since we include a squared term and interactions of these variables, the resulting variables would also be considered endogenous. Therefore, overall, depending on the model specification, we may have up to six endogenous variables.

The following table presents the endogenous variables and their respective instruments:

| Endogenous | Instruments | Definition |
|------------------|-------------|---|
| E_{1j}, E_{2j} | $HORSE_i$ | Horsepower |
| | $DVCO2_i$ | Deviation from European emissions standards |
| | $PRPAS_i$ | Past fuel prices (year of acquisition of vehicle 1) |

When there is squared terms or interactions, the instruments are modified accordingly.

Three specifications tests are computed to assess the validity of our instruments: Hausman (endogeneity), weakness of instruments and over-identification restrictions.

Testing for Endogeneity

The endogeneity Durbin-Wu-Hausman (DWH) test is based in the difference $\hat{\beta}_{2SLS} - \hat{\beta}_{OLS}$. It tests the null hypothesis $E(x'\epsilon) = 0$, under the assumption of homoskedasticity. If the explanatory variables (X) and the instruments (Z) are exogenous, the only difference between the OLS and 2SLS estimates would be the error term. This test is not robust to heteroskedasticity and the computation is cumbersome. Therefore, we performed the regression-based endogeneity test, which is easily computed and can be adapted to be robust to heteroskedasticity (Wooldridge, 2010).

Suppose that E_{ij} is the only potentially endogenous explanatory variable. Assuming all instruments are exogenous, we want to test: $H_0 : Cov(E_{ij}, \epsilon_j) = 0$ (for $i = 1, 2$), against the alternative that E_{ij} is correlated to ϵ_j . To compute this test, we run the first stage regressions (Equation (1)) and extract the residuals \hat{u}_j . Then, we run an augmented

version of equation (3) including the estimated residuals:

$$\ln(VKT_{1j}) = \beta_0 + \beta_1 \ln E_{1j} + \beta_2 \ln E_{2j} + \beta_3 \ln(Pf_{1j}) + X_j + \rho_j \hat{u}_j + \epsilon_j$$

Finally, we obtain the t statistic on \hat{u}_j . If we reject the null hypothesis that $\rho_j = 0$, then we have evidence of endogeneity of E_{ij} , therefore we should use an instrumental variable approach.

This test can be easily extended to several potentially endogenous explanatory variables. Furthermore, if heteroskedasticity is suspected, we can simply perform the regression with robust standard errors.

We adapt the previous test for several endogenous variables, up to $k = 6$ depending on the model specification.

Table 12 presents the output of the endogeneity tests for the 6 potentially endogenous variables (depending on the model specification). We see that at least one of the coefficients for ρ_j^k (where $k = 1, \dots, 6$) is statistically significant in every model, except for models M6 and M7, when using the sub-sample of one vehicle. Thus, the later we estimated by OLS, the former were estimated by 3SLS.

Test for Overidentifying Restrictions

The test for overidentifying restrictions, is used to test the validity of instruments (uncorrelated with ϵ_j) when they exceed the number of endogenous explanatory variables. The test consist in comparing the 2SLS estimator using all instruments to 2SLS using a subset that just identifies equation. If all instruments are valid, the only difference between the two estimates would be the error term. Just as before, this test is not robust to heteroskedasticity and the computation is cumbersome. Sargan (1958) develop a regression-based test for overidentifying restrictions (Wooldridge, 2010).

The null hypothesis is $H_0 : E(\epsilon_j, \mathbf{Z}) = 0$, where $\mathbf{Z} = \{Z_{ij}, X_j'\}$ is the vector of instruments from equation (1), and follows the assumption of homoskedasticity. To compute this test,

Table 12: Regression-based endogeneity test

| | <i>Vehicle-Kilometers traveled</i> | |
|-----------------------|---|-----------------|
| | M2 | M3 |
| <i>Residuals for:</i> | | |
| FE_1 | 0.06 (0.12) | -0.05 (0.13) |
| FE_2 | 0.03 (0.02) | 0.03 (0.02) |
| | M4 | M5 |
| <i>Residuals for:</i> | | |
| FE_1 | -5.80 (1.79)*** | -0.02 (0.12) |
| FE_1^2 | 1.02 (0.31)*** | |
| $FE_1 \times RUR$ | | -0.02 (0.05) |
| $FE_1 \times PAR$ | | 0.01 (0.06) |
| FE_2 | -0.67 (0.46) | 0.06 (0.03)* |
| FE_2^2 | 0.24 (0.16) | |
| $FE_2 \times RUR$ | | -0.07 (0.04) |
| $FE_2 \times PAR$ | | -0.08 (0.06) |
| | M6 | M7 |
| | <i>One vehicle (S-Sample 1)</i> | |
| <i>Residuals for:</i> | | |
| FE_1 | -2.12 (1.70) | -0.03 (0.17) |
| FE_1^2 | 0.40 (0.30) | |
| $FE_1 \times RUR$ | | -0.05 (0.07) |
| $FE_1 \times PAR$ | | -0.02 (0.07) |
| | <i>More than One vehicle (S-Sample 2)</i> | |
| <i>Residuals for:</i> | | |
| FE_1 | -6.83 (3.48)* | -0.35 (0.19)* |
| FE_1^2 | 1.17 (0.63)* | |
| $FE_1 \times RUR$ | | 0.04 (0.10) |
| $FE_1 \times PAR$ | | 0.26 (0.13)** |
| FE_2 | 0.53 (0.36) | 0.10 (0.06) |
| FE_2^2 | -0.08 (0.09) | |
| $FE_2 \times RUR$ | | -0.10 (0.09) |
| $FE_2 \times PAR$ | | -0.33 (0.11)*** |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

The other explanatory variables are identical to those in tables 4,5 and 6, respectively.

first, we run the following regression:

$$\hat{\epsilon}_j = \delta_0 + \mathbf{Z} + v_j$$

Where $\hat{\epsilon}_j$ are the 2SLS residuals.

Then, we compute the statistics is $NR_\epsilon^2 \sim \chi_{m-k}^2$, where R_ϵ^2 is the usual R -squared, m is the number of instruments and k , the number of endogenous variables. If we reject the null hypothesis, the instruments are no valid.

Table 13 presents the results of the Sargan-Hausman for overidentifying restrictions. We see that we fail to reject the null hypothesis, meaning that the over-identification restrictions are valid.

Table 13: Sargan-Hausman for overidentifying restrictions

| | Sample | DF | Statistic | p-value |
|----|-------------------|----|-----------|---------|
| M2 | | 1 | 1.874 | 0.171 |
| M3 | | 1 | 1.927 | 0.165 |
| M4 | | 1 | 0.254 | 0.614 |
| M5 | | 1 | 1.968 | 0.161 |
| M6 | <i>S-Sample 1</i> | 2 | 0.555 | 0.758 |
| M6 | <i>S-Sample 2</i> | 1 | 0.001 | 0.968 |
| M7 | <i>S-Sample 1</i> | 1 | 1.618 | 0.203 |
| M7 | <i>S-Sample 2</i> | 1 | 0.280 | 0.5969 |

Test for Weak Instruments

This test tells us whether an instrument is relevant in the procedure. Under the null hypothesis, the coefficient all instruments is not significantly different from zero. We use the F -test of the first stage regression to determine the instruments strength.

In the next section we present the regression output for the fuel economy equations, where we can see the strength of the instruments.

D Estimates for the endogenous variables

Table 14: Estimates for Fuel economy of all vehicles in the household, M2-M3

| | M2 | | M3 | |
|---------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE (1)</i> | <i>FE (2)</i> | <i>FE (1)</i> | <i>FE (2)</i> |
| <i>HORSE</i> ₁ | -0.16 (0.01) ^{***} | -0.08 (0.04) [*] | -0.43 (0.01) ^{***} | -0.08 (0.04) ^{**} |
| <i>DVCO2</i> ₁ | -0.41 (0.00) ^{***} | -0.01 (0.03) | | |
| <i>HORSE</i> ₂ | -0.00 (0.00) | 1.30 (0.01) ^{***} | -0.01 (0.00) ^{**} | 1.31 (0.01) ^{***} |
| <i>PRPAS</i> ₂ | | | -0.02 (0.03) | -0.38 (0.10) ^{***} |
| <i>PRI</i> | -1.16 (0.02) ^{***} | -0.02 (0.13) | -1.18 (0.04) ^{***} | 0.00 (0.13) |
| <i>DNBUS</i> | 0.00 (0.00) | 0.03 (0.01) ^{**} | 0.00 (0.00) | 0.03 (0.01) ^{**} |
| <i>DNTRA</i> | -0.00 (0.00) | 0.03 (0.01) ^{***} | -0.00 (0.00) | 0.03 (0.01) ^{***} |
| <i>ATMIN</i> | 0.01 (0.00) ^{***} | -0.00 (0.02) | 0.01 (0.01) ^{**} | -0.00 (0.02) |
| <i>MINC</i> | 0.01 (0.00) | 0.06 (0.02) ^{**} | 0.01 (0.01) [*] | 0.06 (0.02) ^{***} |
| <i>AGE</i> | -0.02 (0.01) ^{**} | 0.04 (0.04) | 0.01 (0.01) | 0.03 (0.04) |
| <i>EMPL</i> | 0.00 (0.00) | -0.08 (0.03) ^{***} | -0.00 (0.01) | -0.08 (0.03) ^{***} |
| <i>HIGSC</i> | 0.00 (0.01) | 0.00 (0.03) | 0.01 (0.01) | 0.01 (0.03) |
| <i>SECSC</i> | 0.00 (0.00) | 0.04 (0.03) | -0.00 (0.01) | 0.03 (0.03) |
| <i>PRISC</i> | 0.01 (0.01) | -0.01 (0.04) | 0.01 (0.01) | -0.02 (0.04) |
| <i>NOSC</i> | -0.00 (0.01) | -0.06 (0.04) | -0.02 (0.01) | -0.06 (0.04) |
| <i>TYP2</i> | -0.00 (0.00) | -0.03 (0.03) | 0.00 (0.01) | -0.03 (0.03) |
| <i>TYP3</i> | -0.01 (0.01) [*] | -0.03 (0.04) | -0.01 (0.01) | -0.03 (0.04) |
| <i>TYP4</i> | 0.01 (0.01) [*] | -0.00 (0.05) | -0.01 (0.01) | -0.00 (0.05) |
| <i>TYP5</i> | -0.01 (0.01) | -0.02 (0.06) | 0.00 (0.02) | -0.02 (0.06) |
| <i>RUR</i> | 0.01 (0.00) ^{**} | -0.00 (0.03) | 0.02 (0.01) ^{***} | -0.01 (0.03) |
| <i>PAR</i> | -0.02 (0.01) ^{***} | -0.04 (0.03) | -0.03 (0.01) ^{***} | -0.04 (0.03) |
| <i>OUT</i> | -0.03 (0.02) ^{**} | 0.04 (0.09) | -0.04 (0.03) [*] | 0.04 (0.09) |
| <i>FIRM</i> | 0.05 (0.02) ^{**} | 0.07 (0.12) | 0.10 (0.03) ^{***} | 0.08 (0.11) |
| <i>OTH</i> | 0.01 (0.02) | 0.10 (0.12) | -0.02 (0.04) | 0.12 (0.12) |
| Intercept | 3.59 (0.05) ^{***} | -0.84 (0.26) ^{***} | 3.76 (0.08) ^{***} | -0.84 (0.26) ^{***} |
| Adj. R ² | 0.77 | 0.76 | 0.36 | 0.76 |
| Observations | 4628 | 4628 | 4628 | 4628 |

^{***} $p < 0.01$; ^{**} $p < 0.05$; ^{*} $p < 0.1$. All variables are in logarithms, unless otherwise specified.
FE: Fuel economy. M2: Odometer readings, 3SLS. M3: Declared distance, 3SLS.

Table 15: Estimates for Fuel economy of all vehicles in the household, M4

| | M4 | | | |
|--|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE</i> (1) | <i>FE</i> ² (1) | <i>FE</i> (2) | <i>FE</i> ² (2) |
| <i>HORSE</i> ₁ | 0.45 (0.06) ^{***} | 2.10 (0.34) ^{***} | -0.40 (0.27) | -1.12 (0.85) |
| <i>HORSE</i> ₁ ² | -0.19 (0.02) ^{***} | -0.92 (0.09) ^{***} | 0.09 (0.07) | 0.25 (0.23) |
| <i>DVCO</i> ₂ ₁ | -0.06 (0.00) ^{***} | -0.36 (0.01) ^{***} | 0.00 (0.00) | -0.01 (0.02) |
| <i>HORSE</i> ₂ | -0.01 (0.00) [*] | -0.03 (0.02) | 1.30 (0.01) ^{***} | 3.74 (0.04) ^{***} |
| <i>PRPAS</i> ₂ | -0.00 (0.02) | 0.03 (0.12) | -0.38 (0.10) ^{***} | -1.83 (0.31) ^{***} |
| <i>PRI</i> | -1.22 (0.03) ^{***} | -7.05 (0.17) ^{***} | -0.03 (0.13) | -0.21 (0.41) |
| <i>DNBUS</i> | 0.00 (0.00) [*] | 0.03 (0.01) [*] | 0.03 (0.01) ^{**} | 0.08 (0.03) ^{**} |
| <i>DNTRA</i> | 0.00 (0.00) | 0.01 (0.01) | 0.03 (0.01) ^{***} | 0.09 (0.03) ^{***} |
| <i>ATMIN</i> | 0.00 (0.00) | 0.02 (0.02) | 0.00 (0.02) | -0.01 (0.05) |
| <i>OPT</i> | 0.04 (0.01) ^{***} | 0.24 (0.03) ^{***} | -0.06 (0.02) ^{**} | -0.18 (0.07) ^{**} |
| <i>MINC</i> | 0.04 (0.07) | 0.20 (0.41) | 0.94 (0.32) ^{***} | 3.44 (1.02) ^{***} |
| <i>MINC</i> ² | -0.00 (0.00) | -0.01 (0.03) | -0.06 (0.02) ^{***} | -0.21 (0.07) ^{***} |
| <i>AGE</i> | 0.04 (0.17) | -0.09 (0.94) | -0.80 (0.73) | -2.84 (2.31) |
| <i>AGE</i> ² | -0.01 (0.02) | 0.01 (0.12) | 0.11 (0.10) | 0.38 (0.31) |
| <i>EMPL</i> | -0.00 (0.01) | -0.01 (0.04) | -0.09 (0.03) ^{***} | -0.32 (0.10) ^{***} |
| <i>HIGSC</i> | 0.01 (0.01) | 0.03 (0.04) | -0.00 (0.03) | 0.05 (0.10) |
| <i>SECSC</i> | -0.00 (0.01) | -0.02 (0.04) | 0.02 (0.03) | 0.12 (0.09) |
| <i>PRISC</i> | 0.01 (0.01) | 0.06 (0.05) | -0.03 (0.04) | -0.06 (0.13) |
| <i>NOSC</i> | -0.01 (0.01) | -0.04 (0.05) | -0.08 (0.04) [*] | -0.21 (0.13) |
| <i>TYP</i> ₂ | -0.00 (0.01) | -0.02 (0.03) | -0.02 (0.03) | -0.05 (0.08) |
| <i>TYP</i> ₃ | -0.01 (0.01) | -0.04 (0.05) | -0.03 (0.04) | -0.08 (0.13) |
| <i>TYP</i> ₄ | -0.01 (0.01) | -0.02 (0.06) | -0.01 (0.05) | -0.02 (0.16) |
| <i>TYP</i> ₅ | 0.01 (0.01) | 0.02 (0.08) | -0.02 (0.06) | -0.08 (0.19) |
| <i>RUR</i> | 0.01 (0.01) [*] | 0.06 (0.03) [*] | -0.01 (0.03) | -0.00 (0.08) |
| <i>PAR</i> | -0.02 (0.01) ^{***} | -0.13 (0.04) ^{***} | -0.04 (0.03) | -0.11 (0.09) |
| <i>OUT</i> | -0.04 (0.02) [*] | -0.22 (0.11) [*] | 0.03 (0.09) | 0.08 (0.28) |
| <i>FIRM</i> | 0.08 (0.03) ^{***} | 0.44 (0.15) ^{***} | 0.10 (0.11) | 0.25 (0.36) |
| <i>OTH</i> | -0.01 (0.03) | -0.02 (0.16) | 0.14 (0.12) | 0.32 (0.39) |
| Intercept | 2.82 (0.43) ^{***} | 9.29 (2.38) ^{***} | -2.37 (1.86) | -8.62 (5.86) |
| Adj. R ² | 0.62 | 0.64 | 0.76 | 0.72 |
| Observations | 4628 | 4628 | 4628 | 4628 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. All variables are in logarithms, unless otherwise specified.
 FE: Fuel economy. FE²: Squared Fuel economy. M4: Quadratic effects, 3SLS.

Table 16: Estimates for Fuel economy of all vehicles in the household, M5

| | M5 | | |
|--|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE (1)</i> | <i>FE (1) × Rural</i> | <i>FE (1) × Paris</i> |
| <i>HORSE</i> ₁ | −0.17 (0.01) ^{***} | −0.59 (0.02) ^{***} | −0.36 (0.02) ^{***} |
| <i>HORSE</i> ₁ × <i>RUR</i> | 0.01 (0.00) ^{**} | 1.57 (0.01) ^{***} | 0.01 (0.01) [*] |
| <i>HORSE</i> ₁ × <i>PAR</i> | −0.01 (0.00) ^{**} | 0.03 (0.01) ^{***} | 1.51 (0.01) ^{***} |
| <i>HORSE</i> ₂ | 0.00 (0.00) | −0.01 (0.01) | −0.00 (0.01) |
| <i>HORSE</i> ₂ × <i>RUR</i> | −0.01 (0.00) | 0.04 (0.01) ^{***} | −0.02 (0.01) [*] |
| <i>HORSE</i> ₂ × <i>PAR</i> | −0.01 (0.01) | −0.01 (0.01) | 0.03 (0.01) ^{***} |
| <i>DVCO</i> ₂ ₁ | −0.40 (0.00) ^{***} | −0.10 (0.01) ^{***} | −0.11 (0.01) ^{***} |
| <i>PRI</i> | −1.15 (0.02) ^{***} | −0.37 (0.05) ^{***} | −0.24 (0.04) ^{***} |
| <i>DNBUS</i> | 0.00 (0.00) | −0.00 (0.00) | 0.01 (0.00) [*] |
| <i>DNTRA</i> | 0.00 (0.00) | 0.01 (0.00) ^{**} | −0.01 (0.00) [*] |
| <i>ATMIN</i> | 0.01 (0.00) ^{***} | 0.01 (0.01) [*] | 0.01 (0.01) |
| <i>OPT</i> | 0.03 (0.00) ^{***} | 0.01 (0.01) | 0.00 (0.01) |
| <i>MINC</i> | 0.01 (0.06) | −0.03 (0.13) | 0.31 (0.11) ^{***} |
| <i>MINC</i> ² | −0.00 (0.00) | 0.00 (0.01) | −0.02 (0.01) ^{***} |
| <i>AGE</i> | −0.21 (0.13) | −0.36 (0.29) | 0.02 (0.25) |
| <i>AGE</i> ² | 0.03 (0.02) | 0.05 (0.04) | −0.01 (0.03) |
| <i>EMPL</i> | −0.00 (0.01) | 0.01 (0.01) | −0.00 (0.01) |
| <i>HIGSC</i> | 0.00 (0.01) | 0.01 (0.01) | −0.02 (0.01) |
| <i>SECSC</i> | 0.01 (0.00) | 0.03 (0.01) ^{**} | −0.02 (0.01) ^{**} |
| <i>PRISC</i> | 0.01 (0.01) | 0.05 (0.02) ^{***} | −0.00 (0.01) |
| <i>NOSC</i> | −0.00 (0.01) | 0.02 (0.02) | −0.02 (0.01) |
| <i>TYP</i> ₂ | −0.00 (0.00) | −0.03 (0.01) ^{***} | −0.01 (0.01) |
| <i>TYP</i> ₃ | −0.01 (0.01) [*] | −0.07 (0.02) ^{***} | 0.02 (0.01) |
| <i>TYP</i> ₄ | 0.01 (0.01) [*] | −0.10 (0.02) ^{***} | 0.05 (0.02) ^{***} |
| <i>TYP</i> ₅ | −0.01 (0.01) | −0.10 (0.02) ^{***} | 0.01 (0.02) |
| <i>OUT</i> | −0.03 (0.02) [*] | −0.04 (0.04) | 0.03 (0.03) |
| <i>FIRM</i> | 0.05 (0.02) ^{**} | 0.02 (0.05) | 0.05 (0.04) |
| <i>OTH</i> | 0.01 (0.02) | 0.01 (0.05) | −0.11 (0.04) ^{**} |
| Intercept | 3.93 (0.33) ^{***} | 1.90 (0.75) ^{**} | −0.54 (0.64) |
| Adj. R ² | 0.77 | 0.96 | 0.96 |
| Observations | 4628 | 4628 | 4628 |

^{***} $p < 0.01$; ^{**} $p < 0.05$; ^{*} $p < 0.1$. All variables are in logarithms, unless otherwise specified.
FE: Fuel economy. M5: Fuel economy by zone, 3SLS.

Table 17: Estimates for Fuel economy of all vehicles in the household, M5, continuation.

| | M5 | | |
|--|-----------------|-----------------------|-----------------------|
| | <i>FE (2)</i> | <i>FE (2) × Rural</i> | <i>FE (2) × Paris</i> |
| <i>HORSE</i> ₁ | −0.05 (0.04) | −0.05 (0.03)* | −0.00 (0.02) |
| <i>HORSE</i> ₁ × <i>RUR</i> | −0.01 (0.02) | 0.05 (0.01)*** | −0.00 (0.01) |
| <i>HORSE</i> ₁ × <i>PAR</i> | −0.01 (0.02) | −0.00 (0.01) | 0.02 (0.01)** |
| <i>HORSE</i> ₂ | 1.30 (0.02)*** | −0.03 (0.01)** | 0.00 (0.01) |
| <i>HORSE</i> ₂ × <i>RUR</i> | 0.01 (0.03) | 1.35 (0.02)*** | −0.00 (0.01) |
| <i>HORSE</i> ₂ × <i>PAR</i> | −0.03 (0.03) | 0.01 (0.02) | 1.30 (0.01)*** |
| <i>DVCO</i> ₂₁ | −0.02 (0.03) | 0.01 (0.02) | −0.01 (0.01) |
| <i>PRI</i> | −0.04 (0.13) | −0.06 (0.08) | 0.03 (0.05) |
| <i>DNBUS</i> | 0.03 (0.01)** | 0.00 (0.01) | 0.00 (0.00) |
| <i>DNTRA</i> | 0.03 (0.01)*** | 0.01 (0.01) | 0.00 (0.00) |
| <i>ATMIN</i> | 0.00 (0.02) | −0.01 (0.01) | 0.01 (0.01) |
| <i>OPT</i> | −0.06 (0.02)** | −0.05 (0.01)*** | 0.00 (0.01) |
| <i>MINC</i> | 0.86 (0.33)*** | 0.25 (0.21) | 0.28 (0.13)** |
| <i>MINC</i> ² | −0.05 (0.02)** | −0.01 (0.01) | −0.02 (0.01)** |
| <i>AGE</i> | −0.79 (0.74) | −0.38 (0.47) | −0.18 (0.28) |
| <i>AGE</i> ² | 0.11 (0.10) | 0.05 (0.06) | 0.03 (0.04) |
| <i>EMPL</i> | −0.09 (0.03)*** | −0.04 (0.02)* | −0.02 (0.01)* |
| <i>HIGSC</i> | −0.00 (0.03) | 0.01 (0.02) | 0.00 (0.01) |
| <i>SECSC</i> | 0.03 (0.03) | 0.03 (0.02)* | 0.01 (0.01) |
| <i>PRISC</i> | −0.03 (0.04) | −0.01 (0.03) | −0.00 (0.02) |
| <i>NOSC</i> | −0.07 (0.04)* | −0.04 (0.03) | 0.01 (0.02) |
| <i>TYP</i> ₂ | −0.03 (0.03) | 0.01 (0.02) | 0.01 (0.01) |
| <i>TYP</i> ₃ | −0.03 (0.04) | 0.00 (0.03) | 0.01 (0.02) |
| <i>TYP</i> ₄ | −0.01 (0.05) | 0.00 (0.03) | 0.01 (0.02) |
| <i>TYP</i> ₅ | −0.02 (0.06) | 0.01 (0.04) | −0.00 (0.02) |
| <i>OUT</i> | 0.04 (0.09) | 0.05 (0.06) | 0.02 (0.03) |
| <i>FIRM</i> | 0.08 (0.12) | −0.05 (0.07) | 0.08 (0.04)* |
| <i>OTH</i> | 0.14 (0.12) | 0.03 (0.08) | −0.03 (0.05) |
| Intercept | −2.42 (1.87) | −0.40 (1.18) | −0.75 (0.72) |
| Adj. R ² | 0.76 | 0.83 | 0.81 |
| Observations | 4628 | 4628 | 4628 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. All variables are in logarithms, unless otherwise specified.
FE: Fuel economy. M5: Fuel economy by zone, 3SLS.

Table 18: Sample selection equation

| | <i>More than one vehicle</i> |
|---|------------------------------|
| Diesel | 0.08 (0.05) |
| Vehicle age | 0.14 (0.03)*** |
| Vehicle weight | -0.33 (0.09)*** |
| Vehicle horsepower | 0.19 (0.10)* |
| New vehicle | -0.01 (0.06) |
| Exempt vehicle tax | -0.03 (0.07) |
| Bonus/malus | 0.19 (0.36) |
| Number of licenses ^(a) | 0.88 (0.05)*** |
| Daily travel time | -0.00 (0.00)* |
| Commute trips ^(a) | 0.07 (0.03)** |
| Regular trips ^(a) | -0.10 (0.02)*** |
| Leisure trips ^(a) | -0.01 (0.03) |
| Monthly income | 0.46 (0.06)*** |
| Household size | 0.88 (0.14)*** |
| Number of active persons ^(a) | -0.24 (0.05)*** |
| Number of children ^(a) | 0.19 (0.05)*** |
| Internship | -0.37 (0.75) |
| Student | 0.43 (0.42) |
| Unemployed | -0.04 (0.17) |
| Retired | 0.08 (0.10) |
| Stay-home | -0.23 (0.40) |
| Other | -0.08 (0.28) |
| <i>DNBUS</i> | 0.15 (0.03)*** |
| <i>DNTRA</i> | 0.09 (0.02)*** |
| <i>HIGSC</i> | -0.03 (0.08) |
| <i>SECSC</i> | -0.04 (0.06) |
| <i>PRISC</i> | -0.26 (0.09)*** |
| <i>NOSC</i> | -0.33 (0.10)*** |
| <i>TYP2</i> | -0.05 (0.06) |
| <i>TYP3</i> | -0.64 (0.10)*** |
| <i>TYP4</i> | -0.56 (0.12)*** |
| <i>TYP5</i> | -0.33 (0.14)** |
| <i>RUR</i> | 0.02 (0.06) |
| <i>PAR</i> | -0.39 (0.07)*** |
| <i>OUT</i> | -0.10 (0.24) |
| <i>FIRM</i> | 0.31 (0.27) |
| <i>OTH</i> | 0.39 (0.29) |
| (Intercept) | -4.46 (0.87)*** |

^(a) standardize.

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

All variables are in logarithms, unless otherwise specified.

Table 19: Estimates for Fuel economy of all vehicles in the household, M6

| | M6 | | | |
|--|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE (1)</i> | <i>FE² (1)</i> | <i>FE (2)</i> | <i>FE² (2)</i> |
| <i>HORSE</i> ₁ | 0.53 (0.10) ^{***} | 2.50 (0.53) ^{***} | 0.28 (0.41) | 0.70 (1.44) |
| <i>HORSE</i> ₁ ² | -0.21 (0.03) ^{***} | -1.02 (0.14) ^{***} | -0.06 (0.11) | -0.18 (0.38) |
| <i>DVCO</i> ₂ ₁ | -0.06 (0.00) ^{***} | -0.36 (0.01) ^{***} | -0.03 (0.01) ^{***} | -0.09 (0.03) ^{***} |
| <i>HORSE</i> ₂ | -0.01 (0.01) | -0.06 (0.06) | -0.45 (0.05) ^{***} | -1.77 (0.17) ^{***} |
| <i>DVCO</i> ₂ ₂ | -0.00 (0.00) [*] | -0.01 (0.01) [*] | 0.21 (0.01) ^{***} | 0.56 (0.02) ^{***} |
| <i>PRI</i> | -1.17 (0.05) ^{***} | -6.80 (0.27) ^{***} | -0.09 (0.21) | -0.60 (0.74) |
| <i>DNBUS</i> | 0.00 (0.01) | 0.01 (0.03) | 0.05 (0.02) [*] | 0.16 (0.09) [*] |
| <i>DNTRA</i> | 0.01 (0.00) | 0.03 (0.02) | 0.03 (0.02) [*] | 0.11 (0.06) [*] |
| <i>ATMIN</i> | 0.00 (0.01) | 0.03 (0.03) | -0.01 (0.03) | -0.06 (0.10) |
| <i>OPT</i> | 0.05 (0.01) ^{***} | 0.27 (0.05) ^{***} | -0.05 (0.04) | -0.19 (0.13) |
| <i>MINC</i> | 0.28 (0.16) [*] | 1.42 (0.87) | 1.82 (0.68) ^{***} | 6.72 (2.38) ^{***} |
| <i>MINC</i> ² | -0.02 (0.01) [*] | -0.09 (0.05) | -0.11 (0.04) ^{***} | -0.41 (0.15) ^{***} |
| <i>AGE</i> | 0.50 (0.34) | 2.34 (1.89) | -1.92 (1.47) | -6.88 (5.18) |
| <i>AGE</i> ² | -0.06 (0.05) | -0.30 (0.25) | 0.27 (0.20) | 0.94 (0.69) |
| <i>EMPL</i> | -0.01 (0.02) | -0.02 (0.08) | -0.04 (0.06) | -0.15 (0.23) |
| <i>HIGSC</i> | 0.01 (0.01) | 0.04 (0.07) | 0.04 (0.05) | 0.19 (0.18) |
| <i>SECSC</i> | -0.01 (0.01) | -0.08 (0.06) | 0.07 (0.04) | 0.31 (0.15) ^{**} |
| <i>PRISC</i> | 0.01 (0.02) | 0.02 (0.09) | 0.03 (0.07) | 0.14 (0.25) |
| <i>NOSC</i> | 0.01 (0.02) | 0.03 (0.10) | -0.00 (0.08) | 0.08 (0.27) |
| <i>TYP</i> ₂ | -0.01 (0.01) | -0.05 (0.05) | 0.02 (0.04) | 0.09 (0.14) |
| <i>TYP</i> ₃ | -0.04 (0.02) ^{**} | -0.21 (0.11) [*] | 0.15 (0.08) [*] | 0.48 (0.30) |
| <i>TYP</i> ₄ | -0.05 (0.03) ^{**} | -0.23 (0.14) | 0.22 (0.11) ^{**} | 0.81 (0.39) ^{**} |
| <i>TYP</i> ₅ | -0.02 (0.03) | -0.11 (0.15) | -0.00 (0.12) | -0.06 (0.42) |
| <i>RUR</i> | 0.02 (0.01) [*] | 0.09 (0.05) [*] | 0.02 (0.04) | 0.10 (0.14) |
| <i>PAR</i> | 0.00 (0.01) | -0.00 (0.07) | -0.02 (0.06) | -0.06 (0.20) |
| <i>OUT</i> | -0.04 (0.05) | -0.26 (0.26) | -0.05 (0.20) | -0.14 (0.72) |
| <i>FIRM</i> | 0.11 (0.04) ^{**} | 0.61 (0.23) ^{***} | 0.07 (0.18) | 0.14 (0.64) |
| <i>OTH</i> | 0.00 (0.04) | 0.05 (0.22) | -0.11 (0.17) | -0.46 (0.59) |
| Inverse Mills ratio | 0.02 (0.01) | 0.08 (0.08) | -0.04 (0.06) | -0.16 (0.22) |
| Intercept | 0.84 (0.90) | -0.82 (4.94) | -2.03 (3.85) | -8.23 (13.53) |
| Adj. R ² | 0.60 | 0.47 | 0.63 | 0.33 |
| Observations | 1851 | 1851 | 1851 | 1851 |

^{***} $p < 0.01$; ^{**} $p < 0.05$; ^{*} $p < 0.1$. All variables are in logarithms, unless otherwise specified.

FE: Fuel economy. FE²: Squared Fuel economy. M6: Sample selection correction, no interactions, 3SLS.

Table 20: Estimates for Fuel economy of all vehicles in the household, M7

| | M7 | | |
|--|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE (1)</i> | <i>FE (1) × Rural</i> | <i>FE (1) × Paris</i> |
| <i>HORSE</i> ₁ | −0.46 (0.02) ^{***} | −0.80 (0.03) ^{***} | −0.31 (0.02) ^{***} |
| <i>HORSE</i> ₁ × <i>RUR</i> | 0.01 (0.01) | 1.54 (0.01) ^{***} | −0.00 (0.01) |
| <i>HORSE</i> ₁ × <i>PAR</i> | −0.00 (0.01) | 0.03 (0.01) ^{**} | 1.47 (0.01) ^{***} |
| <i>DVCO</i> ₂ (Log) | −0.00 (0.00) | −0.01 (0.00) [*] | −0.00 (0.00) |
| <i>DVCO</i> ₂ × <i>RUR</i> | 0.00 (0.00) | 0.02 (0.00) ^{***} | −0.00 (0.00) |
| <i>DVCO</i> ₂ × <i>PAR</i> | −0.00 (0.00) | −0.00 (0.01) | 0.02 (0.00) ^{***} |
| <i>DVCO</i> ₂ (<i>PRI</i> | −1.15 (0.06) ^{***} | −0.54 (0.09) ^{***} | −0.18 (0.06) ^{***} |
| <i>DNBUS</i> | 0.01 (0.01) | −0.00 (0.01) | 0.02 (0.01) ^{***} |
| <i>DNTRA</i> | 0.01 (0.01) ^{**} | 0.02 (0.01) ^{**} | −0.00 (0.01) |
| <i>ATMIN</i> | 0.01 (0.01) | 0.01 (0.01) | 0.01 (0.01) |
| <i>OPT</i> | 0.07 (0.01) ^{***} | 0.03 (0.02) [*] | −0.01 (0.01) |
| <i>MINC</i> | 0.34 (0.20) [*] | 0.19 (0.29) | 0.34 (0.20) [*] |
| <i>MINC</i> ² | −0.02 (0.01) [*] | −0.01 (0.02) | −0.02 (0.01) |
| <i>AGE</i> | 0.40 (0.43) | 0.25 (0.63) | 0.17 (0.44) |
| <i>AGE</i> ² | −0.05 (0.06) | −0.03 (0.08) | −0.02 (0.06) |
| <i>EMPL</i> | −0.04 (0.02) ^{**} | −0.01 (0.03) | −0.04 (0.02) [*] |
| <i>HIGSC</i> | 0.00 (0.02) | 0.02 (0.02) | −0.03 (0.02) [*] |
| <i>SECSC</i> | −0.02 (0.01) [*] | 0.03 (0.02) [*] | −0.04 (0.01) ^{***} |
| <i>PRISC</i> | 0.02 (0.02) | 0.04 (0.03) | −0.03 (0.02) |
| <i>NOSC</i> | −0.01 (0.02) | −0.00 (0.03) | −0.04 (0.02) [*] |
| <i>TYP2</i> | −0.00 (0.01) | −0.04 (0.02) ^{**} | 0.00 (0.01) |
| <i>TYP3</i> | −0.04 (0.02) [*] | −0.03 (0.04) | 0.00 (0.03) |
| <i>TYP4</i> | −0.08 (0.03) ^{***} | −0.10 (0.05) ^{**} | 0.02 (0.03) |
| <i>TYP5</i> | −0.04 (0.03) | −0.10 (0.05) [*] | 0.01 (0.04) |
| <i>OUT</i> | 0.01 (0.06) | 0.04 (0.09) | 0.01 (0.06) |
| <i>FIRM</i> | 0.11 (0.05) ^{**} | 0.00 (0.08) | 0.02 (0.05) |
| <i>OTH</i> | −0.02 (0.05) | −0.02 (0.07) | −0.07 (0.05) |
| Inverse Mills ratio | 0.03 (0.02) [*] | 0.01 (0.03) | 0.06 (0.02) ^{***} |
| Intercept | 1.53 (1.12) | 0.26 (1.65) | −1.40 (1.15) |
| Adj. R ² | 0.38 | 0.96 | 0.96 |
| Observations | 1851 | 1851 | 1851 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. All variables are in logarithms, unless otherwise specified.
FE: Fuel economy. M7: Sample selection correction, interactions, 3SLS.

Table 21: Estimates for Fuel economy of all vehicles in the household, M7, continuation

| | M7 | | |
|---|-----------------------------|-----------------------------|-----------------------------|
| | <i>FE (2)</i> | <i>FE (2) × Rural</i> | <i>FE (2) × Paris</i> |
| <i>HORSE</i> ₁ | −0.08 (0.06) | −0.48 (0.04) ^{***} | −0.17 (0.03) ^{***} |
| <i>HORSE</i> ₁ × <i>RUR</i> | 0.03 (0.02) | 1.14 (0.02) ^{***} | −0.00 (0.01) |
| <i>HORSE</i> ₁ × <i>PAR</i> | −0.01 (0.03) | 0.04 (0.02) [*] | 1.01 (0.01) ^{***} |
| <i>DVCO</i> ₂ (Log) | 0.08 (0.01) ^{***} | −0.05 (0.01) ^{***} | −0.02 (0.00) ^{***} |
| <i>DVCO</i> ₂ × <i>RUR</i> | −0.02 (0.01) [*] | 0.20 (0.01) ^{***} | −0.00 (0.00) |
| <i>DVCO</i> ₂ × <i>PAR</i> | 0.02 (0.01) | −0.00 (0.01) | 0.25 (0.01) ^{***} |
| <i>DVCO</i> ₂ (<i>PRI</i>) | −0.13 (0.20) | −0.12 (0.15) | −0.02 (0.09) |
| <i>DNBUS</i> | 0.04 (0.02) | −0.01 (0.02) | 0.02 (0.01) [*] |
| <i>DNTRA</i> | 0.03 (0.02) | 0.02 (0.01) [*] | 0.01 (0.01) |
| <i>ATMIN</i> | −0.01 (0.03) | −0.01 (0.02) | 0.00 (0.01) |
| <i>OPT</i> | −0.01 (0.04) | −0.04 (0.03) | −0.01 (0.02) |
| <i>MINC</i> | 2.19 (0.66) ^{***} | 0.88 (0.47) [*] | 0.66 (0.28) ^{**} |
| <i>MINC</i> ² | −0.14 (0.04) ^{***} | −0.05 (0.03) [*] | −0.04 (0.02) ^{**} |
| <i>AGE</i> | −2.41 (1.43) [*] | −1.38 (1.03) | −0.36 (0.61) |
| <i>AGE</i> ² | 0.33 (0.19) [*] | 0.18 (0.14) | 0.05 (0.08) |
| <i>EMPL</i> | −0.02 (0.06) | −0.01 (0.05) | −0.05 (0.03) [*] |
| <i>HIGSC</i> | 0.04 (0.05) | 0.03 (0.04) | 0.02 (0.02) |
| <i>SECSC</i> | 0.07 (0.04) [*] | 0.07 (0.03) ^{**} | 0.02 (0.02) |
| <i>PRISC</i> | 0.02 (0.07) | 0.04 (0.05) | −0.02 (0.03) |
| <i>NOSC</i> | −0.03 (0.07) | −0.03 (0.05) | 0.01 (0.03) |
| <i>TYP</i> ₂ | 0.05 (0.04) | 0.03 (0.03) | 0.01 (0.02) |
| <i>TYP</i> ₃ | 0.15 (0.08) [*] | 0.03 (0.06) | 0.11 (0.03) ^{***} |
| <i>TYP</i> ₄ | 0.24 (0.11) ^{**} | 0.00 (0.08) | 0.15 (0.05) ^{***} |
| <i>TYP</i> ₅ | 0.02 (0.12) | 0.00 (0.08) | 0.01 (0.05) |
| <i>OUT</i> | 0.01 (0.20) | 0.13 (0.14) | 0.05 (0.08) |
| <i>FIRM</i> | 0.03 (0.18) | −0.12 (0.13) | 0.01 (0.08) |
| <i>OTH</i> | −0.12 (0.16) | 0.00 (0.12) | −0.11 (0.07) |
| Inverse Mills ratio | −0.12 (0.06) [*] | −0.05 (0.04) | 0.02 (0.03) |
| Intercept | −2.41 (3.74) | −0.04 (2.69) | −1.87 (1.59) |
| Adj. R ² | 0.52 | 0.88 | 0.90 |
| Observations | 1851 | 1851 | 1851 |

****p* < 0.01; ***p* < 0.05; **p* < 0.1.

****p* < 0.01; ***p* < 0.05; **p* < 0.1. All variables are in logarithms, unless otherwise specified.

FE: Fuel economy. M7: Sample selection correction, interactions, 3SLS.

Chapter 2

Rebound effects in the collective household

This chapter has been written in autonomy.

Parts of this chapter were presented at: the 6th Annual Conference of the French Association of Environmental and Resource Economists, Rennes, August 29-30, 2019; 68th Annual meeting of the French Economic Association, Orléans, June 17-19, 2019; the 3rd Annual Meeting of the Society of Economics of the Household (SEHO), Lisbon (Portugal), June 27-28, 2019.

Energy efficiency policies aim at reducing greenhouse gas emissions (GHG) by lowering energy consumption. However, the increase in demand for energy following an efficiency improvement, known as the rebound effect, partially reduce energy savings and the policy impact. Traditionally, researchers have approached the rebound effect by modeling household energy demand on the basis of the standard household theory (unitary model). Nevertheless, recent literature suggests that the resource allocation process within the household may have an impact in the consumption decisions, an effect that traditional models fail to capture. In this chapter, we propose a collective household model that allows for heterogeneous preferences inside the household. We model the demand for energy services and analyze how the heterogeneous preferences affects the demand for such services and the rebound effect. We make a simulation and find that the direct rebound effect can be up to 54% higher than traditional measures, when accounting for

heterogeneous preferences inside the household. We find empirical evidence that expenditures on energy public services vary according to the preferences of the household leader.

Keywords: Rebound effect, Collective Approach, Energy consumption, Public energy services, Household Behavior

1 Introduction

In their latest report, the IPCC (2018) has concluded that the Paris agreement's target, namely limit global warming to 1.5°C above pre-industrial levels, can only be achieved by halving Greenhouse Gas (GHG) emissions by 2030. Energy efficiency is often seen as a cost-effective way to reduce GHG associated to energy consumption. Therefore, governments encourage larger incentives aiming at energy efficiency improvements, arguing that this can be a way to achieve energy savings, all by providing individuals with the same level of energy services (IPCC, 2018).

Despite all the potential benefits of energy efficiency policies, their impact is limited by the rebound effect. When an energy system becomes more efficient, the real cost of unit energy service may fall. In such case, people would have incentives to consume more energy services, thus increasing the demand for energy. This increase in the demand for energy, or rebound effect, will determine the actual effectiveness of these policies at reducing energy consumption and the associated GHG (Sorrell et al., 2009; Sterner, 2012).

To better estimate the energy-savings potential of energy policies, it is essential to understand the determinants of energy consumption. Demand for energy is determined by households preferences for goods and services. Recent findings estimate that 40% of energy consumption in the residential sector is determined by technical factors and about 33% is determined by socioeconomic characteristics such as revenue, household age, and tenure status (Bakaloglou and Charlier, 2019).

The literature on the rebound effect (e.g., Chan and Gillingham, 2015; Chitnis and Sorrell, 2015; Sorrell et al., 2009) has mainly focused on the technical factor leading to the changes in energy demand. Only recently some studies have considered heterogeneous responses based in socioeconomic characteristics (e.g. Frondel et al., 2012; Galvin, 2015; Hymel and Small, 2015). Nevertheless, there is still a lot of things to understand. For instance, Kriström (2008) argues that even household sharing socio-demographic characteristics or having the same kind of devices may consume energy at different levels. One possible

explanation for this is the fact that members of a same household have heterogeneous preferences that add up to different final consumption decisions. In particular, household demand decisions are the result of a negotiation process, in which individual preferences within a household are weighted according to each individual "influence" (Vermeulen, 2002).

The analysis of the effect that individual preferences have on energy demand can shed some lights into the importance of household heterogeneity and the variability in energy consumption (Bakaloglou and Charlier, 2019). This is especially relevant, given the magnitude of households' demand for energy. Indeed, in 2016, the residential sector¹ makes up for a quarter of final energy consumption in the European Union (EU) and demand is expected to rise by 2040 (Bishop, 2015). Furthermore, transports accounts for over 30% of energy use, with light-duty vehicles (i.e. households demand for fuel) consuming more energy than all modes of freight transportation combined (EIA, 2016).

Traditionally, researchers have approached the rebound effect by modeling household energy demand based in the standard household theory. This approach is known as the unitary model. The main underlying hypotheses of this model are (a) that households act as a single decision-making unit, regardless of the number of household members, and (b) that only total exogenous income explains household behavior (income pooling) (Vermeulen, 2002).

Critics of this approach point out several unsatisfactory elements in this theory. First, one could argue that different members of the household have their own rational preference, not necessarily identical. According to Arrow's impossibility theorem, a group of individuals not necessarily behave as a single one. Moreover, the income pooling hypothesis has been repeatedly rejected in empirical studies, suggesting that the way income is distributed among households members (after a negotiation process) can affect consumption decisions (For more details see Donni, 2008; Vermeulen, 2002).

This study mainly investigates how the heterogeneous preferences inside a household

¹Households: energy use for space and water heating, space cooling, cooking, lighting and electrical appliances and other end-uses, excluding transportation

affect the household energy consumption decisions. We model the collective demand for energy services and estimate the rebound effect through the simulation of several scenarios. Furthermore, we use French data on household expenditure to test some of the model hypothesis.

This chapter has three contributions to the microeconomic literature on rebound. First, we integrate the collective household setting into the theoretical discussion of the rebound effect. Second, we propose a new methodology for the measurement of the rebound effect. Third, we test some of the main hypothesis of this new setting and examine the implications of this new setting for the current environmental policies relying on energy efficiency.

The present work amplifies the current rebound literature by including the collective household and the public good dimension as presented by Cherchye et al. (2012). We consider heterogeneous preferences inside the household, we model the energy consumption of a household as a public good and we measure the direct rebound effect. This new methodology allows to better grasp the impact of heterogeneities into rebound behaviors. To the best of our knowledge, among the few theoretical works addressing the microeconomics of the rebound effect (e.g., Chan and Gillingham, 2015; Hunt and Ryan, 2015), none of these include intra-household dynamic in their model.

The theoretical results suggest that the intra-household decision process can define the size and direction (positive or negative) of the rebound effect. Therefore, by ignoring the intra-household dynamic, rebound effect estimates can be misleading, either under or over-estimating the effect. In particular, we find a direct rebound effect corresponding to the one that is identified in the current literature. In addition, we find a indirect rebound effect arising from the negotiation process. This indirect effect can be either positive or negative depending on the power distribution among household members. Meaning that the direct rebound effect can be increased, compensated or even completely absorbed depending on each individual's preferences and the power distribution among them.

The structure of the chapter is as follows. Section 2 presents the traditional theoretical

approach for the rebound effect. Section 3 lays the basis for the new theoretical framework, based in the collective household theory. Section 4 presents a collective analysis of welfare and its implications. Section 5 presents an empirical application. Section 6 summarize the data sources. Section 7 presents the empirical findings. Finally, section 8 concludes and addresses future extensions.

2 Literature review

Evidence of the rebound effect was first presented by William Stanley Jevons in 1865 while assessing the evolution of the demand for coal. Ever since, multiple theoretical and empirical studies have provided further evidence on its existence (Gillingham et al., 2016; Sorrell et al., 2009).

Literature distinguishes three types of rebound effect arising from the decrease in the effective price of an energy service due to an improvement in energy efficiency. First, the *direct rebound effect*, when consumption of that particular energy service increases. Second, the *indirect rebound effect*, corresponding to changes in demand for *other* goods, that also require energy, following the efficiency improvement. Third, the *economy-wide rebound effect* corresponds to the sum of all the direct and indirect effects, that will eventually lead to changes in prices of intermediate and final goods throughout the economy as well as quantity adjustments (Sorrell et al., 2009).

Table 1 presents some of the most recent and relevant estimates of the rebound effect based on household demand models. These studies are organized according to the region, the measure for the rebound and the type of the rebound.

The rebound effects can be measured in terms of energy, carbon or GHG emissions. Since carbon/emissions intensity of energy system varies, the relative magnitude of these rebounds may also differ. Furthermore, the indirect rebound effect may be affected by the embodied energy (carbon/GHG) of goods and services. In other words, households consume indirectly the energy used during the production process of good and services (Chitnis et al., 2014).

Table 1: More recent and relevant studies on the residential rebound effect

| Author | Region | Measure | Type of rebound | Estimates |
|-----------------------------|-------------|----------------|-----------------|------------|
| Schmitz and Madlener (2020) | Germany | CO2 | Combined | -7.3%-121% |
| Chitnis et al. (2020) | UK | GHG | Combined | -12%-69% |
| Linn (2016) | US | Miles traveled | Direct | 20%-40% |
| Aydin et al. (2017) | Netherlands | Energy | Direct | 27%-41% |
| Freire-González (2017) | EU-27 | Energy | Combined | 73%-81%. |
| Chitnis and Sorrell (2015) | UK | GHG | Combined | 41% -78% |
| Chitnis et al. (2014) | UK | GHG | Combined | 0%-106% |
| Druckman et al. (2011) | UK | GHG | Indirect | 12%-34% |
| Freire González (2010) | Spain | Electricity | Direct | 73%-81%. |

Some studies base their estimates of the rebound based in single-energy service models, such like we did in Chapter 1. This methodology is widely used in the estimation of the rebound effect for road transport, the energy service for which we find the most estimates of the rebound effect. The estimated magnitude vary widely depending on the type of data and the methodology. Estimates go from 0% up to 40% for the United States (Linn, 2016; Sorrell et al., 2009) and they double when it comes to European data (e.g. Frondel et al., 2012). Freire González (2010) estimate the rebound effect for residential electricity consumption in Catalonia. He finds a direct rebound of 36% in the short-run and 49% in the long-run.

More recent studies have included multiple services in the modeling of the rebound effect, namely, by estimating a household demand model (Sorrell, 2012). Such a model represents the household demand for commodities (including the relevant energy services), as a function of total expenditure, commodity prices and other variables. In this setting, household expenditures need to be aggregated into a limited number of commodity groups to reduce the number of coefficients to be estimated (Chitnis and Sorrell, 2015). This methodology allows to measure the direct and indirect rebound effects, by estimating the own and cross-price elasticities for a given energy service. These estimates are sensitive to the measure of the rebound (energy or GHG for instance) and to the number of commodity groups considered. Estimates for vehicle use tend to be on the higher bounds, ranging around 68% (Chitnis et al., 2020, 2014) in some occasions close to 100% (Schmitz and

Madlener, 2020). For heating, it ranges between 30% and 70% (Aydin et al., 2017; Chitnis et al., 2020)².

Most of these studies (e.g. Brännlund et al., 2007; Chitnis and Sorrell, 2015) define the different categories of household expenditures by type of energy (e.g. electricity, gas) rather than the energy service (e.g. heating, cooking). This could potentially lead to biased estimates. First, the use of the commodity price elasticity as a proxy to the rebound effect can be misleading. Second, in practice one type of energy can be used to produce several energy services, for instance both cooking and heating appliances can be electric, which would introduce additional bias to the measure. Nevertheless, due to lack of data, this is the best approximation for the size of the rebound (Freire-González, 2017).

A drawback with household demand models, used to analyze multiple energy services, is that the number of parameter to estimate is high, which limits the degrees of freedom and leaves little space to explore heterogeneous rebounds.

Recent work has brought into light the importance of household heterogeneity in explaining the variability in energy consumption (e.g. Bakaloglou and Charlier, 2019; Krishnamurthy and Kriström, 2015). Empirical evidence has found heterogeneous rebound effects with respect to some household characteristics. For instance, Greene (2012) and Hymel and Small (2015) find that rebound effects may decline as households get wealthier. Aydin et al. (2017) found heterogeneous rebound effects, that are determined by household wealth and income. They estimate the rebound for space heating in the Netherlands and find 27% among homeowners and 41% percent among tenants.

When controlling for the number of vehicles, evidence suggests that single-vehicle households (probably those with lower driving intensity) tend to have higher rebound effects (e.g. Frondel et al., 2012; Greene et al., 1999). Furthermore, Galvin (2015) finds that females commuters to jobs in one German region show significantly higher rebound effects than their male counterparts. However, simply accounting for household characteristics may not be enough to capture the real impact of heterogeneities into energy demand. As

²Notice that these measures are not comparable due to differences in the methodology

Kriström (2008) suggests, even households sharing a set of socio-demographic characteristics, may reach different demand decisions.

A key element in the modeling of household heterogeneity is the fact that the rebound literature is based on the traditional unitary models. It implies that household preferences are usually represented by a single utility function, although there are no particular reasons to assume that all household members share a same set of preferences. In a multi-person household, the consumption decisions are a result of negotiation between household individuals. Individual preferences will prevail depending on how much influence (or distribution power) each individual has inside the household (Chiappori, 1992). For instance, the findings presented by Galvin (2015) may suggest that different configurations in distribution power in a male-female household can have significant impacts on the final energy consumption.

The collective household allows heterogeneous preference for all individuals in one household and let us consider the public nature of energy services inside a household, for instance heating, and the scale economies associated to it. These two elements can shed some light into the variability of energy consumption and rebound behaviors. Consider the case where negotiation in higher income households is more egalitarian (than in lower income households) and that at least one member of the household has strong preferences for the use of a greener transportation mode. This could explain the lower rebound for this type of households and could help policy-makers to redirect policy incentives.

So far, only few studies have attempted to explain household demand for (some) energy services by considering the existence of heterogeneities within the household and none of these studies have focused on the rebound effect. Bargain and Donni (2012), Browning et al. (2013), and Vermeulen and Watteyne (2006) use collective household theory and household demand models to explain demand for public goods inside the household. They all consider at least one energy service (transports) as a commodity group in their model. They find a significant difference between energy expenditure elasticity for different household compositions, namely between two-member household and single person

household lead by a female.

This chapter contributes to the microeconomic literature on rebound in two ways: First, by integrating the collective household setting into the theoretical discussion of the rebound effect. Second, by proposing a new methodology for the measurement of the rebound effect. In particular, we consider heterogeneous preferences within the household as well as between them, we model the energy consumption inside a household as a public good and we measure the direct rebound effect. This new methodology allows to better grasp the impact of heterogeneities into rebound behaviors. To the best of our knowledge, among the few theoretical works addressing the microeconomics behind the rebound effect (e.g., Chan and Gillingham, 2015; Hunt and Ryan, 2015), none of these include intra-household aspect in the model.

In the next section we lay the basis for the collective model for energy demand. We then present the rebound effect under this new framework. Furthermore, we show the results from a simulation exercise and the empirical test of some of the main hypothesis of this modeling. Finally, we discuss the implication of these results draw some conclusions.

3 A collective model for energy demand

In this section, we develop the foundations for a collective household model with home production, based in the setting presented by (Cherchye et al., 2012). For the sake of simplicity, the model presented here do not consider labor supply. Throughout, superscripts refer to household members and subscripts refer to goods.

3.1 General framework

Consider a two-member household ($i = 1, 2$) that derives their utility from the consumption of three types of goods: an energy intensive composite good, corresponding to flights and public transportation, denoted k^i ; a composite non-energy good denoted by c^i and a set of public energy services, denoted by \mathbf{G} . The public energy services are further distinguished between home energy services, such as heating, cooking or lighting, G_h and

transportation (i.e demand for driving), denoted G_t . Then, the public consumption can be represented by the vector of public services $\mathbf{G} = \{G_h, G_t\}$.

Notice that, the notion of private (e.g. meals) and public (e.g. heating) good within the household follows the usual definition in terms of exclusivity and rivalry. For simplicity, we exclude the possibility of impure goods, meaning that each good is either purely private or purely public.

In this framework, any public energy service is obtained from the combination of energy and an energy conversion appliance of a given efficiency level (Sorrell, 2012). The production of such services follow the standard assumption of cost minimizing. Let $\mathbf{E} = \{E_h, E_t\}$ be a vector of energy inputs required to produce the energy services and $\mathbf{S} = \{S_h, S_t\}$ a vector of production shifters. Cherchye et al. (2012) define a production shifter as a variable that affects individual preferences only through the household production technology. Here, we argue that the efficiency level of energy conversion devices acts as a production shifter.

Following the rebound literature, we can define the production function for the household services as subutility functions given by:

$$\begin{aligned} G_t &= G_t(E_t, S_t) = E_t S_t \\ G_h &= G_h(E_h, S_h) = E_h S_h \end{aligned} \tag{1}$$

The subutility representing the home energy services and the transportation can be interpreted as the utility provided for the comfort at home and the use of mobility. In view of identification, we assume that there is at least one production shifter for each energy service. Under this assumptions, the efficiency level is an exogenous factor rather than an objective variable in the household optimization program.

The household allocate its income, I , to expenditures on the level of public consumption \mathbf{G} and to private consumption of k^i and c^i for each individual i . The household budget

constraint is given by:

$$c^1 + c^2 + p_k^1 k^1 + p_k^2 k^2 + p_t E_t + p_h E_h \leq I \quad (2)$$

Where the respective prices of k^i , E_h and E_t are p_k^i , p_h and p_t . The price of the non-energy composite good is normalized to one. Further, the income allocation depends on the individual preferences of each member and their power within the household. Individual preferences of member i are represented by the utility function noted u^i :

$$u^i = u^i(c^i, k^i, G_h(E_h, S_h), G_t(E_t, S_t)) \quad (3)$$

The utility function u^i depends on the private consumption, k^i and c^i , and the public consumption \mathbf{G} . Following Cherchye et al. (2012), the functions $u^i(\cdot)$ and the subutility functions G_h and G_t are assumed increasing and concave in all its arguments. Furthermore, the household production technologies described by the subutility functions are characterized by constant returns to scale.

Following the standard collective household setting Chiappori (1992; 1988), we assume that individuals inside the household reach a Pareto-efficient intrahousehold allocation, determined by the parameter ϕ . Such allocation results from the solution to the following optimization program:

$$\begin{aligned} \max_{c^1, c^2, k^1, k^2, E_h, E_t} & \phi(p_k^1, p_k^2, p_t, p_h, I, Z) u^1(c^1, k^1, G_t(E_t, S_t), G_h(E_h, S_h)) \\ & + (1 - \phi(p_k^1, p_k^2, p_t, p_h, I, Z)) u^2(c^2, k^2, G_t(E_t, S_t), G_h(E_h, S_h)) \end{aligned} \quad (4)$$

Subject to constraints (1) and (2). The Pareto weight ϕ represents the relative power of

individual 1 inside the household. This function is assumed to be continuously differentiable in all its arguments. This individual's power position depends on the prices of the goods and services p_k^1 , p_k^2 , p_t and p_h , the household income I and a vector of distribution factors Z . By definition, a distribution factor is a variable that affects the distribution of power but not the individual preferences or the budget constraint (Browning and Chiapori, 1998). Examples of distribution factors include the ratio between the spouses wages, their age difference or any nonlabor income (e.g. subsidies).

The optimal levels of private and public consumption are observable functions of prices, income, distribution factors and production shifters ($i = 1, 2$):

$$\begin{aligned}
 c^i &= c^i(p_k^1, p_k^2, p_t, p_h, I, Z, S) \\
 k^i &= k^i(p_k^1, p_k^2, p_t, p_h, I, Z, S) \\
 E_h &= E_h(p_k^1, p_k^2, p_t, p_h, I, Z, S) \\
 E_t &= E_t(p_k^1, p_k^2, p_t, p_h, I, Z, S)
 \end{aligned} \tag{5}$$

The system of equations (5) is completely observed. The remaining of this section presents the two-stage process of the household decision.

3.2 Individual preferences and the sharing rule

The program (4) can be expressed as a two-stage process. First, individuals agree on public expenditures as well as the particular distribution of I . Second, each member freely chooses the level of consumption of the composite goods, conditional on the level of public expenditures.

Given the cost minimization in the household production process and the properties of the subutility functions $G_j(E_j, S_j)$ ($j = \{h, t\}$), there will be unique values for the inputs in the household production process that generates the outputs $\mathbf{G}^* = \{G_h^*, G_t^*\}$.

Let $\mathbf{E}^* = \{E_h^*, E_t^*\}$ be the vector of optimal input values.

The residual income, defined as the remaining share of income after choosing the level of public services, will be $\bar{I} = I - \sum_j p_j E_j^*$ at the optimal level. Therefore, we define the conditional sharing rule as the share of total income allocated to each individual after the purchase of the energy service (hence, the conditioning). This share is given by δ^1 and δ^2 , where:

$$\delta^i(p_k^1, p_k^2, p_t, p_h, I, Z, S) = c^i + p_k^i k^i \quad (6)$$

δ^i represents the share of total income allocated to i , after the purchase of the energy service. We can then re-write the budget constraint (2) as:

$$\delta^1 + \delta^2 = I - p_h E_h^* - p_t E_t^* \quad (7)$$

Then, the individual's maximization program for the second stage allocation problem can be defined as:

$$\begin{aligned} \max_{c^i, k^i} \quad & U^i(c^i, k^i, \mathbf{G}^*) \\ \text{subject to} \quad & \delta^i = c^i + p_k^i k^i \end{aligned} \quad (8)$$

This means that each agent maximizes their private consumption under the constraint that they cannot spend more than their share of residual total income.

In addition, program (8) can be expressed in terms of the indirect utility (conditional on \mathbf{G}):

$$\begin{aligned} U^i(c^i, k^i, \mathbf{G}^*) = \min_{\delta^i} \quad & V^i(\delta^i, \mathbf{G}^*) \\ \text{subject to} \quad & \delta^i = c^i + p_k^i k^i \end{aligned} \quad (9)$$

Notice that $V^i(\delta^i, \mathbf{G}^*)$ depends only on i 's preference and it does not directly change with a particular decision process, however, its argument δ^i does.

3.3 Determining the optimal level of public good

In this section, we determine the optimal level of public services and the underlying trade-offs with private consumption.

The optimization program at the first stage of the household decision process can be redefined by using the indirect utility functions. At this stage, the household decides the optimal levels of energy services $\mathbf{G} = \{G_h, G_t\}$ and the underlying sharing rule, $\{\delta^1, \delta^2\}$, which solves the following maximization program:

$$\begin{aligned} \max_{\delta^1, \delta^2, G_h, G_t} \quad & \phi V^1(\delta^1, \mathbf{G}) + (1 - \phi) V^2(\delta^2, \mathbf{G}) \\ \text{s.t.} \quad & \delta^1 + \delta^2 + \sum_j p_j E_j = I \\ & E_j S_j = G_j \end{aligned} \tag{10}$$

The Lagrangian function associated to the collective household maximization program is:

$$\mathcal{L}(\delta^1, \delta^2, G_h, G_t, \lambda) = \phi V^1(\delta^1, \mathbf{G}) + V^2(\delta^2, \mathbf{G}) + \lambda \left(I - \delta^1 - \delta^2 - p_h \frac{G_h}{S_h} - p_t \frac{G_t}{S_t} \right) \tag{11}$$

From (11), we compute the first order conditions:

$$\begin{aligned}
 \frac{\partial \mathcal{L}}{\partial \delta^1} = 0 & \quad \phi \frac{\partial V^1}{\partial \delta^1} - \lambda = 0 \\
 \frac{\partial \mathcal{L}}{\partial \delta^2} = 0 & \quad (1 - \phi) \frac{\partial V^2}{\partial \delta^2} - \lambda = 0 \\
 \frac{\partial \mathcal{L}}{\partial G_h} = 0 & \quad \phi \frac{\partial V^1}{\partial G_h} + (1 - \phi) \frac{\partial V^2}{\partial G_h} - \lambda \frac{p_h}{S_h} = 0 \\
 \frac{\partial \mathcal{L}}{\partial G_t} = 0 & \quad \phi \frac{\partial V^1}{\partial G_t} + (1 - \phi) \frac{\partial V^2}{\partial G_t} - \lambda \frac{p_t}{S_t} = 0 \\
 \frac{\partial \mathcal{L}}{\partial \lambda} = 0 & \quad I - \delta^1 - \delta^2 - p_h \frac{G_h}{S_h} - p_t \frac{G_t}{S_t} = 0
 \end{aligned}$$

Rearranging, we have the following first order conditions :

$$\begin{aligned}
 \phi \frac{\partial V^1}{\partial \delta^1} = (1 - \phi) \frac{\partial V^2}{\partial \delta^2} = \lambda ; & \quad \frac{\partial V^1}{\partial G_j} + (1 - \phi) \frac{\partial V^2}{\partial G_j} = \lambda \frac{p_j}{S_j} & (12) \\
 E_j S_j = G_j ; & \quad \delta^1 + \delta^2 + \sum_j p_j E_j = I \\
 \text{with } j = \{h, t\} &
 \end{aligned}$$

Two important relationships can be drawn from these conditions. First, the Pareto weight can be recovered :

$$\phi = \frac{\partial V^2 / \partial \delta^2}{\partial V^1 / \partial \delta^1 + \partial V^2 / \partial \delta^2} \quad (13)$$

Second, the standard Bowen-Lindahl-Samuelson conditions for the optimal provision of public services in the household:

$$MW P_j^1 + MW P_j^2 = \frac{\partial V^1 / \partial G_j}{\partial V^1 / \partial \delta^1} + \frac{\partial V^2 / \partial G_j}{\partial V^2 / \partial \delta^2} = \frac{p_j}{S_j} \quad (14)$$

The ratio $(\partial V^i / \partial G_j) / (\partial V^i / \partial \delta^i)$ corresponds to i 's marginal willingness to pay (MWP_j^i) for the public good j . Equation (14) implies that the sum of the individuals' marginal willingness to pay must equal the price of the public energy service, which is a function of the energy price and the efficiency.

A generic identification of the model described in (10) only required that we observe (c^i, k^i, E_h, E_t) as functions of $(p_k^1, p_k^2, p_t, p_h, I, Z, S)$.

4 Collective Analysis of Welfare

Having the theoretical framework for collective household behavior, we can now analyze the welfare implications of energy efficiency policies, which can help us to understand energy consumption decisions and the rebound effect within the household.

We want to study how a change in energy efficiency can affect the household demand for public goods \mathbf{G} and the sharing rule δ^i . Furthermore, we want to compute the rebound effect.

First, we present the theoretical derivation of the rebound effect. Then, we do a simulation exercise by using some particular parametric forms for the utility function. Finally, we calibrate the model and present the results.

4.1 Theoretical collective rebound effect

In this section, we characterize the rebound effect under the collective household, by using the results of the previous section.

From (12), we can re-write the first order conditions as :

$$\begin{aligned}
 \phi \frac{\partial V^1}{\partial \delta^1} - (1 - \phi) \frac{\partial V^2}{\partial \delta^2} &= 0 \\
 MWP_j^1 + MWP_j^2 - \frac{p_j}{S_j} &= 0 \\
 E_j S_j - G_j &= 0
 \end{aligned} \tag{15}$$

We want to determine the rebound effect, in other words, we want to find the effect of an efficiency improvement on the household demand for energy services. Recall that we defined the energy efficiency as a production shifter S_j . Then, let $\delta^1 = \delta$ and $\delta^2 = Y - \delta - \sum_j p_j E_j$.

We can then take the full derivative of the system (15) with respect to the energy efficiency. We get the following system:

$$\begin{aligned}
 \frac{\partial G_j}{\partial S_j} \left[\overbrace{\phi \frac{\partial^2 V^1}{\partial \delta^1 \partial G_j} - (1 - \phi) \frac{\partial^2 V^2}{\partial \delta^2 \partial G_j} + (1 - \phi) \frac{\partial^2 V^2}{\partial \delta^2} \frac{p_j}{S_j}}^a \right] + \\
 \frac{\partial \delta}{\partial S_j} \left[\overbrace{\phi \frac{\partial^2 V^1}{\partial \delta^1} + (1 - \phi) \frac{\partial^2 V^2}{\partial \delta^2}}^b \right] &= \overbrace{\left[(1 - \phi) \frac{\partial^2 V^2}{\partial \delta^2} \right]}^c \frac{p_j}{(S_j)^2} G_j \\
 \frac{\partial G_j}{\partial S_j} \left[\overbrace{\frac{\partial MWP_j^1}{\partial G_j} + \frac{\partial MWP_j^2}{\partial G_j} - \frac{\partial MWP_j^2}{\partial \delta^2} \frac{p_j}{S_j}}^d \right] + \\
 \frac{\partial \delta}{\partial S_j} \left[\overbrace{\frac{\partial MWP_j^1}{\partial \delta^1} - \frac{\partial MWP_j^2}{\partial \delta^2}}^e \right] &= - \overbrace{\left[\frac{\partial MWP_j^1}{\delta^2} + \frac{1}{G_j} \right]}^f \frac{p_j}{(S_j)^2} G_j \\
 S_j \frac{\partial E_j}{\partial S_j} + E_j &= \frac{\partial G_j}{\partial S_j}
 \end{aligned} \tag{16}$$

Now, solving the equation system (16) for $\frac{\partial G_j}{S_j}$, $\frac{\partial \delta}{S_j}$ and $\frac{\partial E_j}{S_j}$, we find that, the effect of a change in energy efficiency on the demand for energy services \mathbf{G} and the sharing rule δ^i is given by:

$$\frac{\partial G_j}{\partial S_j} = \Gamma \frac{p_j}{(S_j)^2} G_j; \quad \frac{\partial E_j}{\partial S_j} = \Gamma \frac{E_j}{S_j}; \quad \frac{\partial \delta}{\partial S_j} = -\Lambda \frac{p_j}{(S_j)^2} G_j \quad (17)$$

$$\text{Where } \Gamma = \frac{ce + f}{ae - b} \quad \Lambda = \frac{af + c}{ae - b}$$

As we recall from previous sections, the direct rebound effect is defined as the efficiency elasticity of the demand for public services. In this case, the direct rebound effect is given by:

$$\frac{\partial G_j}{\partial S_j} \frac{S_j}{G_j} = \Gamma \frac{p_j}{S_j} \quad (18)$$

This rebound effect is directly proportional to the implicit price of the energy service. The parameter Γ encompasses the collective household dimension. It depends on the Pareto weights, prices and income. Assume that one individual in the household have a higher preference for the energy service G_j . In that case, the size of rebound would depend on the power of decision that individual has.

In contrast, under the unitary model, these parameters depends only depend on prices and income. These estimations will fail to account for possible amplifying or attenuating effects of the intra-household distribution of power (i.e. the pareto weight).

In the next section we presents a simulation exercise in which we analyze the size and sign of the rebound effect under heterogeneous preferences.

4.2 Simulation of the collective rebound effect

In this section we do a simulation exercise to illustrate the effect of heterogeneous preferences on the estimates of the direct rebound effect. First we present the assumptions made to calibrate the simulation model, then, we discuss the results.

Assumptions

We considered a two-person household in which we represent the preferences by a simple parametric form. We consider three cases. First, we assume identical preferences among households members. This case corresponds to the unitary model and it is the reference case. Second, we assume different preferences, specifically, we assume that individual 1 has a higher preference for the public service G_t than his/her companion. Finally, we assume that individual 1 has a lower preference for the public service than his/her companion.

We then maximize each of the utility functions, subject to the household budget constraint and the household production technology. These constraints are the same regardless of the case considered and are given by Equations (1) and (2).

The unitary preferences are defined by the following Cobb-Douglas function:

$$u(c, k, G_h, G_t) = a \text{Log } c + (1 - a) \text{Log } k + \beta \text{Log } (G_h + \gamma G_t) \quad (19)$$

Where a , β and γ are the parameters of the utility function. Notice that there is no distinction between individual and collective consumption. Therefore, we maximize a single utility function, which is equivalent to a particular case of the collective setting where $\phi = 1$ (or $\phi = 0$, if individual 2 has dominant preferences).

We solve the maximization program given by the utility function (19) subject to the household production functions (1) and the budget constraint (2) presented in section 3.

$$G_t = E_t S_t$$

$$G_h = E_h S_h$$

$$c^1 + c^2 + p_k^1 k^1 + p_k^2 k^2 + p_t E_t + p_h E_h \leq I$$

Afterwards, we find the demand functions for all the goods and services.

The demand functions for the service G_t , in the unitary case, is defined as:

$$G_t = \frac{\gamma S_t S_h I}{\gamma S_h p_t - p_h S_t} \quad (20)$$

The heterogeneous preferences are given by the following utility function:

$$u^i(c^i, k^i, G_h, G_t) = a^i \text{Log } c^i + (1 - a^i) \text{Log } k^i + \beta^i \text{Log } (G_h + \gamma^i G_t) \quad (21)$$

Where a^i , β^i and γ^i are the parameters of the individual utility function.

In this case, there is a distinction between individual and collective consumption. The value of parameters β^i and γ^i are adjusted depending on which individual have a higher preference for G_t . Similarly, we maximize the collective program and find the respective demand functions.

The demand functions for the service G_t , in the collective case, is given by:

$$G_t = \frac{(\beta^1 \gamma^2 \phi(S_t p_h - \gamma^1 S_h p_t) + \beta^2 \gamma^1 (\phi - 1)(\gamma^2 S_h p_t - S_t p_h)) S_h S_t I}{(\beta^2 (\phi - 1) - \beta^1 \phi - 1)(\gamma^1 S_h p_t - S_t p_h)(\gamma^2 p_t S_h - p_h S_t)} \quad (22)$$

From the demand functions (20) and (22), we derive the respective direct rebound effects.

The direct rebound effect for the unitary case is defined as:

$$\eta_S^G = \frac{\partial G_t}{\partial S_t} \frac{S_t}{G_t} = \frac{\gamma S_h p_t}{\gamma S_h p_t - S_t p_h} \quad (23)$$

The direct rebound effect for the collective case is defined as:

$$\eta_S^G = \frac{\partial G_t S_t}{\partial S_t G_t} = S_h p_t \left(\frac{\gamma^1 + \gamma^2}{\gamma^1 S_h p_t - S_t p_h} + \frac{\gamma^1 \gamma^2 (\beta^2 + \beta^1 \phi - \beta^2 \phi)}{\beta^2 \gamma^1 (\phi - 1) (\gamma^2 S_h p_t - S_t p_h) + \beta^1 \gamma^2 \phi (p_h S_t - \gamma^1 S_h p_t)} \right) \quad (24)$$

Model calibration

Now, we calibrate the model and compare the rebound effect of the base line situation (unitary case, $\phi = 1$), to four different scenarios.

As we said before, the preference (higher or lower) for the service G_t depends on the value of parameters β^i and γ^i .

In the second case, where individual 1 has a higher preference for service G_t , the values for parameters β^i and γ^i are: $\beta^1 = \beta^2 = \gamma^1 = 0.5$ and $\gamma^2 = 0.3$.

In the third case, where individual 1 has a lower preference for service G_t , the values for parameters β^i and γ^i are: $\beta^1 = \beta^2 = \gamma^1 = 0.5$ and $\gamma^2 = 1$.

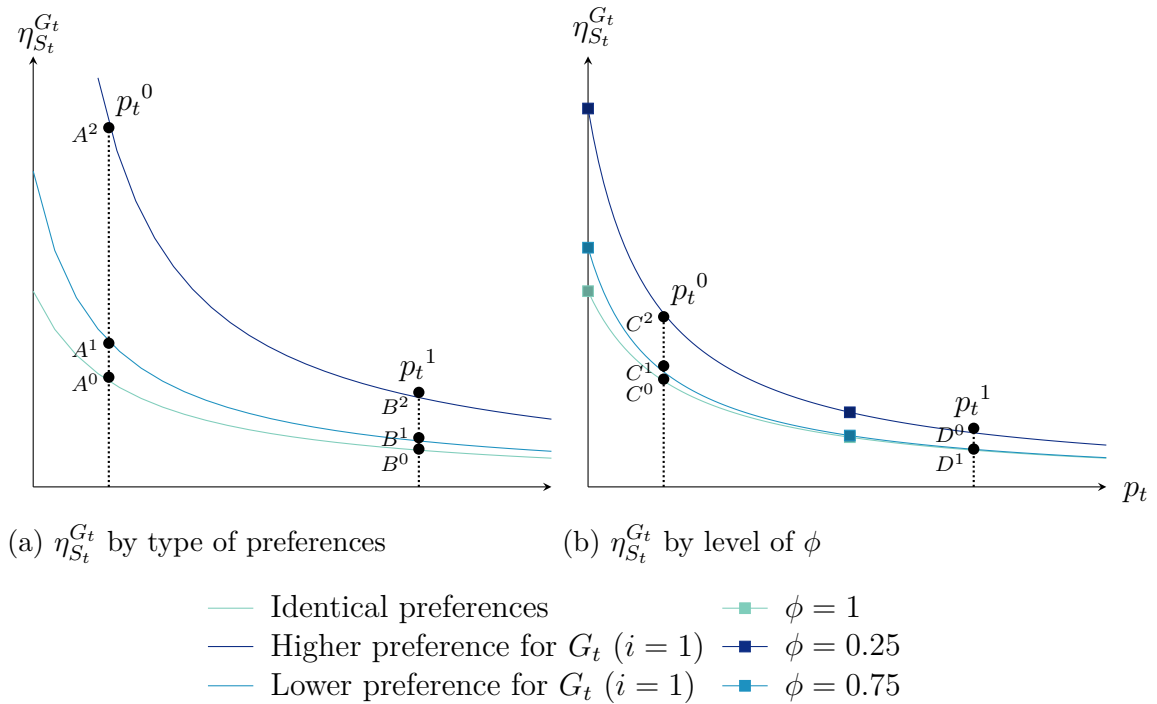
With these conditions, the four scenarios that we compare are:

- Scenario 1: individual 1 have higher preferences for G_t and $\phi = 0.5$
- Scenario 2: individual 1 have lower preferences for G_t and $\phi = 0.5$
- Scenario 3: individual 1 have lower preferences for G_t and $\phi = 0.25$
- Scenario 4: individual 1 have lower preferences for G_t and $\phi = 0.75$

Under the first two scenarios, the power distribution inside the household is fixed, and preferences are different. Under the other two scenarios, preferences are fixed and the power distribution is different.

The parameters for prices, income and efficiency were normalized between zero and one, as to have a continuous demand function. Income I was fixed at 1. The price of the

Figure 1: The rebound effect with heterogeneous preferences inside the household



energy service G_h , p_h , was fixed at 0.1. The levels of efficiency S_t and S_h were fixed at 0.1 and 0.2 respectively.

The simulation was run using the software **Wolfram Mathematica**. The results of this exercise are discussed in the following section.

Simulation results

Figure 1 presents the direct rebound effect for the energy service G_t , measured as the efficiency elasticity of demand, $\eta_{S_t}^{G_t}$. This figure shows that in all cases, the rebound effect decreases as the energy price increases.

The left panel (Figure 1.a) shows how the rebound effect varies when different preferences inside a household are allowed. The lightest line describes the rebound effect under the assumption of identical preferences, this is the base line scenario. This corresponds to the unitary model, in which the household program is described by the maximization of a single utility function, usually that of the individual with the higher relative power inside the household, in this example, individual 1.

The darkest line describes the rebound effect under the assumption that individual 1 has a higher preference for G_t than individual 2. The rebound moves away from that of the unitary case. The dominant preferences in the household (those of individual 1) are heavily leaned towards G_t , which drives up demand. For a given energy price p_t^0 , the rebound effect is 54% larger than it is at the base line (distance A^0A^2). When the energy price increases to p_t^1 , the rebound effect is 11% larger than it is at the base line (distance B^0B^2).

The medium line, describes the rebound effect under the assumption that individual 1 has a lower preference for G_t than individual 2. The rebound is close to the unitary case, because the dominant preferences in the household (those of individual 1) are not in favor of G_t , driving down its demand. For a given energy price p_t^0 , the rebound effect is 8% larger than it is at the base line (distance A^0A^1). When the energy price increases to p_t^1 , the rebound effect is 2% larger than it is at the base line (distance B^0B^1).

Furthermore, the rebound effect can also be affected by the distribution of power inside the household. The right panel (Figure 1.b) illustrates this effect. The lightest line describes again the base line scenario, which corresponds to a parameter $\phi = 1$.

Parting from the assumption that individual 1 has a lower preference for G_t than individual 2, the rebound effect is farther away from the base line scenario when individual 2 has a higher power inside the household than individual 1 ($\phi = 0.25$). The dominant preferences in the household (those of individual 2) are heavily leaned towards G_t , which drives up demand. For a given energy price p_t^0 , the rebound effect is 14% larger than it is at the base line (distance C^0C^2). When the energy price increases to p_t^1 , the rebound effect is 11% larger than it is at the base line (distance C^0C^2).

On the contrary, the rebound effect is very similar to the base line scenario when individual 1 has a higher power inside the household than individual 2 ($\phi = 0.75$), because his preferences are less favorable towards G_t . In this case, it is only 2% higher than the base line scenario when the energy price is p_t^0 , and equal when the energy price is p_t^1 .

5 Empirical application

In this section we do an empirical application based on the theoretical model presented in the section 3.

We compute the empirical (observed) sharing rule in order to test the validity of the collective model using expenditure data for French households in 2010-2011. We exploit a unique dataset which documents individual expenses.

Furthermore, we propose an identification strategy for the collective model and a parametric form. However, due to lack of data on the efficiency of some energy services and prices, this model cannot be implemented to date. A full account this is given in appendix A.

Empirical sharing rule

In this section, we will compute the empirical sharing rule, in order to test the validity of the collective optimization program (10).

This program can be expressed as a two-stage process. First, individuals agree on public expenditures as well as the particular distribution of the residual income (i.e. the household income minus the expenditures on public services). Second, each member freely chooses the level of consumption of the composite good, conditional on the level of public expenditures and the budget constraint.

Starting at the second stage, we identify the underlying sharing rule for a given level of public services G_t^* and G_h^* . The sharing rule represents the household decision process and the individual preferences defined over private consumption.

Let x^i be the the sum of expenditures of individual i on good c^i and k^i . The empirical sharing rule for the individual i is defined as:

$$\hat{\delta}^i = \frac{x^i}{\sum_i x^i} \quad (25)$$

Furthermore, based on the sharing rule, we determine which individual has the more "power" of decision in the household. Recall that the distribution of power or Pareto weight, ϕ , represents the relative power of individual 1 inside the household. This individual's power position depends mainly on the prices of the goods and services, income and distribution factors. Therefore, we assume that the individual with the most power would have the most negotiation power and, subsequently, can have a bigger share of residual income.

Knowing which individual in the household has the more power, we can then assess how the distribution of power affects the demand for energy services.

Thus, we approximate the demand for energy service G_j as a share of the total expenditures on public energy services.

Let \tilde{G}_j be the expenditures on energy service G_j expressed as a share of the total expenditures on energy public services. This share is given by:

$$\tilde{G}_j = \frac{G_j}{\sum_j G_j} \quad \text{for } j \in \{j, h\} \quad (26)$$

This exercise allows us to see how the income sharing determines the demand for energy services. We expect to see significant differences in the demand for public services depending on the individual who has the highest share of income.

The next section presents the data and the results of this estimation.

6 Data description

In this chapter we use French micro-data from the Family Budget Survey (Enquête Budget de famille) of 2010-2011. This dataset was obtained through the Quêtelet-PROGEDO Difussion, a portal to access French Data in human and social sciences.

The Family Budget survey is conducted every five years by the National Statistics Institute of France, Insee. It collects information about household final consumption expenditure on goods and services (mainly), on income and some demographic and socio-economic characteristics. The survey was conducted over a 12-month period from October 2010 to September 2011. The sample consists of ordinary³ households from Metropolitan France and Overseas. Overall, 25 000 households were surveyed, of which 8300 belongs to Overseas France.

Families record every expenditure, its nature and the amount spent, even expenditures other than goods and services, such as taxes, transfers or debt reimbursement. These expenditures are detailed up to 900 expenditure categories. These categories can be matched to the Classification of Individual Consumption According to Purpose (COICOP), for international comparisons.

The data collection process was undertaken over two visits made by the survey taker. These visits take place 8 to 14 days apart. Every member of the household older than 14 year old fills a card to track their everyday purchases. They record every expenditure incurred over a period of 7 days. A card is distributed to every person in the household during the first visit and gather over the second visit.

During the first visit households are asked about socio-demographics; expenditures on durable goods and clothing, trips and personal services (such as education or child care), telecommunications, leisure activities, health, and on gifts and others. During the second visit, households are asked about housing expenses (rent, etc.) and utilities (heating, electricity, etc.); acquisitions of land and house renovations; expenses on transports; purchases

³It excludes nursing homes, religious communities, student residences, prisons, etc.

Table 2: List of variables and expenditure groups

| Variable | Definition | Nature | Expenditures |
|----------|------------------|------------|---|
| c^i | Non-energy goods | Individual | Food and drinks (non-alcoholic) outside the home (restaurant, bar, company restaurant etc.; tobacco products, alcoholic beverages and narcotics; clothing (clothing, shoes, jewelry, etc.); medical expenditures not covered by an insurance; leisure and cultural activities (not including travel); schooling (courses, tuition fees, etc.); personal care and services (hair care, body care, etc.); gifts (to family members, friends, charity, etc.) |
| k^i | Energy goods | Individual | Public transportation and travel |
| G_h | Energy services | Collective | Utilities (heating, electricity, other energies) |
| G_t | Vehicle use | Collective | Transportation costs (gasoline, etc., but no insurances or purchase of transportation means) |

and resales of valuable objects; other expenditures, such as insurance, debt, income taxes or financial fees; finally, household resources, including wages, subsidies, rents, and self-consumption. Furthermore, individuals answer two questionnaires about the less regular expenditures (e.g. durable goods).

For simplicity, we restricted the sample to two-person households with only one private vehicle at their disposal, to ensure the existence of car sharing. Overall, we have 3650 observations.

A unique characteristic of this dataset is that it provides detailed assignable expenditures within the household, which is specially important for the identification of the sharing rule.

Following the theoretical model presented in section 3, we categorize expenditures in four: k^i , c^i , G_h and G_t . Table 2 presents the definition of the four groups, the nature of the variable (individual or collective) and what expenditures are considered for each one.

Notice that households also consume a set of public services non-energy related. These services constitute mostly first necessity goods and services such as food and housing and represent most of the households expenditures. The present work focus solely on energy related public services. Therefore, we excluded the latter group of expenditure from the

Table 3: Summary Statistics, Couples and singles

| Expenditure | Variable | Mean | St. Dev. | Min | Max |
|---------------------------------|-----------------------|------------------------|----------|----------------|-----------|
| Private - Men | $c^1 + p^1 k^1$ | 202.56 | 292.91 | 0.00 | 5,242.24 |
| Private - Women | $c^2 + p^2 k^2$ | 249.62 | 292.27 | 0.00 | 5,222.62 |
| Household services | G_h | 140.83 | 203.68 | 0.00 | 2,688.17 |
| Transports | G_t | 218.10 | 127.98 | 4.80 | 1,680.00 |
| Other household services | | 3 266.98 | 37 076 | 13.33 | 2 155 411 |
| Conditional observed shares | | | | | |
| Men | δ^1 | 0.43 | 0.27 | 0.00 | 1.00 |
| Women | δ^2 | 0.57 | 0.27 | 0.00 | 1.00 |
| Share dominant Men | $\delta^1 > \delta^2$ | 0.39 | | | |
| T-test Mean differences: | | <i>Mean difference</i> | -0.148 | <i>p-value</i> | 0.000 |
| Other household characteristics | | | | | |
| Age - Men | | 59.32 | 16.23 | 18 | 95 |
| Age - Women | | 56.86 | 16.08 | 16 | 95 |
| Total Income | | 38 580 | 25 919 | 19 | 442 151 |

Note: The total number of observations is 3650. However, the variable G_t has only 1843 observations due to missing data.

modeling. This is made under the assumption of weak separability between these other services and the bundle of private and public consumption defined by k^i, c^i, G_h and G_t (Sorrell, 2012). However, we included it in Table 3 for comparison purposes with the expenditures on the energy services categories.

Taxes, credits and expenditures on durable good were excluded from the analysis. Finally, all expenses are normalized to a monthly periodicity.

7 Estimation results

Table 3 reports some summary statistics of the main variables used in our model. The individual private expenditures equal the sum of all the individual expenditures on the categories c^i and k^i presented above. The expenditures on the public services G_h and G_t equal the sum of the respective expenditures on the categories in the public expenditures presented above. Finally, expenditures on other public services correspond to the sum of all other utilities and household expenses not considered in Table 2. This last category of expenditures is included for comparison purposes only, mainly because it covers most of

the household expenditures.

We see that on average, the women in the couple have higher private expenditures (249 euros per month) than their partners (202 euros per month). Expenditures on transportation (G_t) are 1.5 times the expenditures on (energy) household utilities (G_h). Most of the household's expenditures are spent on other public goods: on average, the couples spend about 3 266 euros per month on these goods.

The empirical share rule shows that in average, women take a bigger share of the residual income, 57% against 43% for their partners. As we defined in the in previous sections, the residual income is the remaining of the household income after the purchase of the public goods. We present a t-test of mean difference for the average women-men conditional shares. The mean differences is statistically significant.

Moreover, we compute the proportion of households where the man's share was higher than the woman's share. We find that this is the case in 39 % of the households in the sample. In this sample, women are the "dominant" individual for nearly a third of the households in the sample, meaning that they have a higher income share.

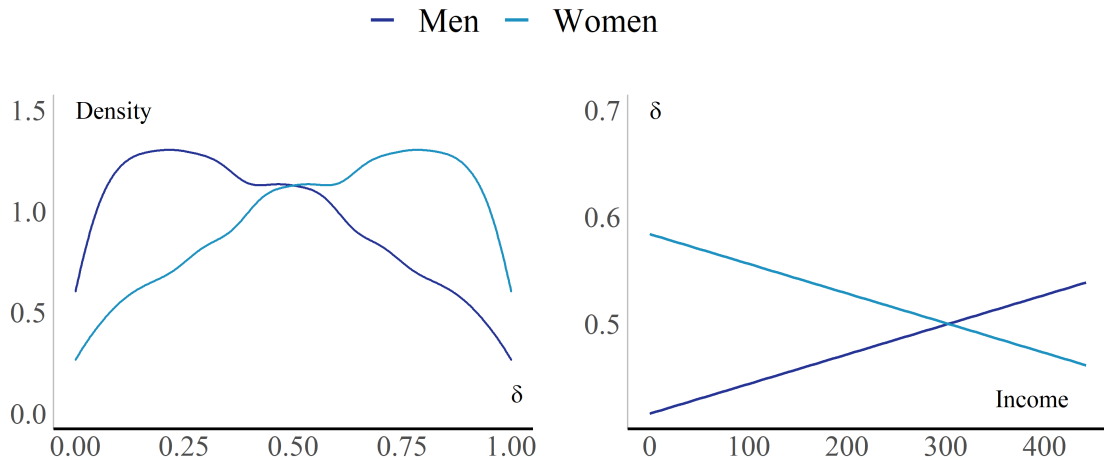
Figure 2 presents the distribution of the sharing rule for men and women in the sample. The left panel (Figure 2a) presents the distribution of the empirical sharing in the sample. The x-axis represents the value of δ^i .

The right panel (Figure 2b) shows the empirical sharing rules per level of income. We see that the higher the income, the more equally distributed. As we showed in table 3, for most of the sample, women are the "dominant" individual in the household. As income increases, the roles inverts and we find that in average, men are "dominant".

This figure shows how income is distributed inside the household. This provides further evidence that the distribution of income inside the household is different and so would be the distribution of power.

Now, we can evaluate how this income allocation affects the demand for the public energy services. In particular, we want to see if a household led by a woman has a different

Figure 2: Empirical sharing rule and income distribution of the residual income



(a) Empirical sharing rule

(b) Income distribution

Reading note: The left panel presents the empirical sharing rule estimated from the individual expenditures on childless couples. The x-axis represents the value of δ^i . The right panel shows the empirical sharing rules per level of income. The curves in this figure represent the average relationship (linear regression) between the sharing rule and annual income (in thousands of euros). We see that the higher the income, the more equally distributed.

Table 4: Test of mean differences

| Expenditure share | Mean difference | p-value |
|-------------------|-----------------|---------|
| \tilde{G}_t | -0.0009 | 0.92 |
| \tilde{G}_h | -0.019 | 0.10 |

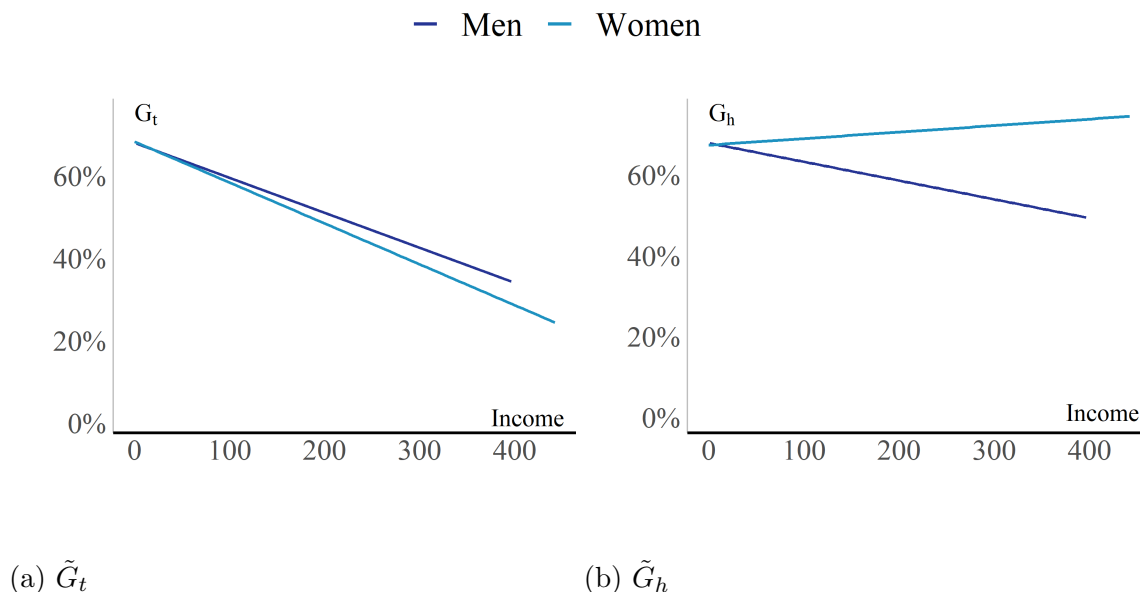
demand than a households led by a man⁴.

Figure 3 presents the relationship between the annual income (in thousands of euros) and the share of expenditures (on public energy services) allocated to transportation \tilde{G}_t and household energy services \tilde{G}_h , by the sex of the dominant individual in the household.

The left panel (Figure 3a) illustrates the share of expenditures on transportation, meaning the expenditures linked to the use of the private vehicle. The overall share of expenditures on transportation decreases with income. This can be related to the discussion presented in section 4 of Chapter 1. We explained that one of the claims of the yellow

⁴In this context, a *household led by a woman (man)* means that, in said household, the woman (man) has a higher income share than her (his) partner.

Figure 3: Demand for energy services by dominant partner



Reading note: The curves show the relationship between the annual income (in thousands of euros) and the shares of expenditures on public energy services allocated to each of the energy service (t , h), by the sex of the dominant individual in the household. The left panel shows the share of expenditures on public energy services allocated to G_t . The right panel shows the share of expenditures on public energy services allocated to G_h .

jackets movements was that lower income households rely more on vehicles for work and transportation compared with wealthier households, which is what this figure describes.

Furthermore, we see that these expenditures represent a higher share in households led by men. The distance to the expenditures of households led by women increases with income. Therefore, we performed a test of mean difference to see the significance of the distance between the expenditures on households led by men and that of households led by women. Table 4 reports the results of the test. The p-value is high, meaning that we fail to reject the null hypothesis of equal means. This result should be read with care, because there is a significant amount of missing values in the variable G_t which could alter the results.

The right panel (Figure 3b) illustrates the share of expenditures on household energy services, mostly expenditures on heating, electricity and gas. In this case, the slope of the curves varies significantly depending who leads the household. Contrary to the expenditures on transportation, the expenditures on household energy services represent

a higher share in households led by women and they increase with income. In households led by men, the share of expenditures on household energy services decreases with income. Similarly, we performed a test of mean difference to see if the distance between the expenditures on households led by men and that of those led by women is significant. The result of this test is shown in table 4. The p-value indicates that we can reject the null hypothesis equality of means with a confidence of 90%.

These results support the leading hypothesis of this chapter, namely, that the rebound effect is sensitive to the distribution of power inside the household. This suggests that the estimates of the rebound effect can be more accurate if the heterogeneous preferences are considered. Nevertheless, the validity of these results are limited to this particular sample, which is not representative of the French population.

8 Conclusions

According to the IPCC (2018), the internationally agreed target for limiting global warming to 1.5°C above pre-industrial levels, can only be achieved by drastically transforming energy systems across all sectors. Today, improvements in energy efficiency are being encouraged and implemented as a way to achieve such energy savings. Despite all the proved benefits of these policies, their impact is limited by the increase in demand for energy following an efficiency improvement, known as the rebound effect, which partially reduces energy savings. It means that effectiveness of the policy at reducing energy consumption and the associated GHG will depend on magnitude of the rebound.

Traditionally, researchers have approached the rebound effect by modeling household energy demand based in the standard household theory, known as the unitary approach. However, several studies have pointed out the limits of this approach, by saying that it fails to account for heterogeneity on preferences among household members and the influence of such differences on household energy consumption decisions. Alternatively, recent research has paid more attention to the collective model. The collective approach provides a theoretical background to account for within household heterogeneity and

income distribution. Moreover, this setting allows for the existence of public or collective services within the household, such as heating.

In this chapter, we propose a new theoretical framework for the rebound effect that enhances the traditional approach by integrating the key elements outlined in the collective household theory. Then, this new framework accounts not only for technical aspects of energy-saving technologies but also for the decision-making process within the household. To the best of our knowledge, this theoretical model is the first to assess the rebound effect from a collective household perspective and to include the public good notion.

The results of the theoretical model suggest that the intra-household decision process can determine the size of the rebound effect through the individual preferences. We did a simulation exercise in which we compare the rebound effect for the unitary and collective households models. We find that the direct rebound effect can be up to 54% higher for the collective setting.

Furthermore, we use French data on household expenditures for 2010-2011 to test the model. A unique characteristic of this data is that it provides detailed assignable expenditures within the household. This feature allows the identification of the sharing rule, which determines the distribution of the remaining household income after the purchase of the collective goods and services.

Moreover, the sharing rule can also give an indication of the individual who has the most "dominant" preferences. It means that the individual getting the bigger share of residual income, may have the most negotiation power and therefore, his/her preferences will determine in a greater measure the final consumption decisions.

We compute the empirical (observed) sharing rule for a sample of 3650 childless couples. We find that, in average, women in the couple take 57% of the residual income after the purchase of the collective goods and services. In addition, women have the dominant preferences in about two third of the households in the sample.

We find evidence that expenditures on energy public services vary with the leader of the

household. In particular, we find that households led by men seem to have a greater share of expenditures on transportation services. While household led by women, have a greater share of expenditures on household energy services (heating, electricity or gas).

Furthermore, the rebound effect depends on the distribution of power inside the household and demand for energy services can significantly change with the preferences of the leading individual in the household. These results imply that more accurate measures of the rebound effect should take into consideration the intra-household heterogeneity. However, so far, the validity of the empirical results are limited to a particular sample, which is not representative of the French population.

In this chapter, we provide further evidence of the importance of heterogeneity in the assessment of the rebound effect and, in general, the public policy evaluation. We show that heterogeneous preferences inside the households may amplify or attenuate the rebound effect. Therefore, by ignoring the intra-household dynamic, rebound effect estimates can be misleading and the actual impact of efficiency policies cannot be accurately assessed.

Appendices

A Identification

The program (10) can be expressed as a two-stage process. First, individuals agree on public expenditures as well as the particular distribution of the residual income (i.e. the household income minus the expenditures on public services). Second, each member freely chooses the level of consumption of the composite good, conditional on the level of public expenditures and the budget constraint.

Starting at the second stage, the aim is to identify the underlying sharing rule for a given level of public services G_t^* and G_h^* , which represents the household decision process and the individual preferences, defined over private consumption (i.e. the individuals utility function).

Chiappori (1992; 1988) shows that the sharing rule and the individual preferences can be recovered by using the variation of prices and residual income. However, as explained by Cherchye et al. (2012), in the presence of public goods, such identification strategy is not possible because the variation of prices and income have an impact on the level of public goods. Therefore, they proved that the variation of (at least one) distribution factor and production shifter can be exploited to achieve identification.

Afterwards, moving into the first stage, we find the Bowen-Lindahl-Samuelson conditions for the optimal provision of public services in the household. Ultimately, this condition will characterize the optimal values for the sharing rule and the public energy services.

Cherchye et al. (2012) show that by observing the system (5) as functions of $(p_k^1, p_k^2, p_t, p_h, I, Z, S)$, the individual preferences and the Pareto weights can be uniquely and generically identified. The indirect utilities are identified up to a strictly increasing transformation, while the Pareto weight is exactly identified.

B Model specification

In this section we present the parametric specification for the theoretical model presented above. Following the parametric model presented in Cherchye et al. (2012), we use the individual indirect utility functions, which is possible thanks to the two-stage representation of the household program.

Following Cherchye et al. (2012), we approximate the preferences by using a PIGLOG indirect utility. Assuming that individual preferences on private consumption, at the second stage of the decision process, can be represented by the following indirect utility functions:

$$v^i(p_k^i, \delta^i, \bar{G}_h, \bar{G}_t) = \frac{\ln(p_k^i + \delta^i) - (\alpha_1^i(d^i) + \alpha_2^i \ln(\bar{G}_h) + \alpha_3^i \ln(\bar{G}_t)) \ln(p_k^i)}{(p_k^i)^{\beta^i}} \quad (27)$$

For $i = 1, 2$, where d^i is a vector of individual taste shifters. The conditional Marshallian demand functions for c^i can be obtained through the Roy's identity $-\frac{\partial v^i / \partial p_k^i}{\partial v^i / \partial \delta^i} = 0$. Thus, we have:

$$\begin{aligned} \frac{\partial v^i}{\partial p_k^i} &= \frac{1}{p_k^i{}^{\beta^i+1}} \left[\frac{p_k^i(1+k^i)}{p_k^i + \delta^i} - \beta^i \ln\left(\frac{p_k^i + \delta^i}{a^i}\right) - A \right] \\ \frac{\partial v^i}{\partial \delta^i} &= \frac{1}{(p_k^i)^{\beta^i} (p_k^i + \delta^i)} \\ -\frac{\partial v^i / \partial p_k^i}{\partial v^i / \partial \delta^i} &= \frac{(p_k^i)^{\beta^i} (p_k^i + \delta^i)}{p_k^i{}^{\beta^i+1}} \left[\frac{p_k^i(1+k^i)}{p_k^i + \delta^i} - \beta^i \ln\left(\frac{p_k^i + \delta^i}{a^i}\right) - A \right] = 0 \end{aligned}$$

Where $A = (\alpha_1^i(D^i) + \alpha_2^i \ln(\bar{G}_h) + \alpha_3^i \ln(\bar{G}_t))$ and $\ln(a^i) = A \ln(p_k^i)$. Finally, the demand functions for the energy and composite private goods are:

$$k^i = \frac{(p_k^i + \delta^i)}{p_k^i} \left[A + \beta^i \ln \left(\frac{p_k^i + \delta^i}{a^i} \right) \right] - 1 \quad (28)$$

$$c^i = (p_k^i + \delta^i) \left[1 - A - \beta^i \ln \left(\frac{p_k^i + \delta^i}{a^i} \right) \right] \quad (29)$$

Now, we move to the first-stage of the decision process, where the household allocates its income to the sharing rule and the expenditures in the public energy services, $(\delta^1, \delta^2, G_h, G_t)$.

The first-stage maximization program, presented in (10), can be written as:

$$\begin{aligned} \max_{\delta^1, \delta^2, G_h, G_t} \quad & \phi \left(\frac{\ln(p_k^1 + \delta^1) - (\alpha_1^1(D^1) + \alpha_2^1 \bar{G}_h + \alpha_3^1 \bar{G}_t) \ln(p_k^1)}{p_k^{1\beta^1}} \right) \\ & + (1 - \phi) \left(\frac{\ln(p_k^2 + \delta^2) - (\alpha_1^2(D^2) + \alpha_2^2 \bar{G}_h + \alpha_3^2 \bar{G}_t) \ln(p_k^2)}{p_k^{2\beta^2}} \right) \\ \text{subject to} \quad & \delta^1 + \delta^2 + p_h G_h + p_t G_t = I \\ & G_t = E_t S_t \\ & G_h = E_h S_h \end{aligned} \quad (30)$$

The Lagrangian function associated to the collective household maximization program, described in (11), becomes:

$$\begin{aligned} \mathcal{L}(\delta^1, \delta^2, G_h, G_t, \lambda) = & \phi \left(\frac{\ln(p_k^1 + \delta^1) - (\alpha_1^1(D^1) + \alpha_2^1 \bar{G}_h + \alpha_3^1 \bar{G}_t) \ln(p_k^1)}{p_k^{1\beta^1}} \right) + \\ & (1 - \phi) \left(\frac{\ln(p_k^2 + \delta^2) - (\alpha_1^2(D^2) + \alpha_2^2 \bar{G}_h + \alpha_3^2 \bar{G}_t) \ln(p_k^2)}{p_k^{2\beta^2}} \right) + \\ & \lambda \left(I - \delta^1 - \delta^2 - p_h \frac{G_h}{S_h} - p_t \frac{G_t}{S_t} \right) \end{aligned} \quad (31)$$

The first order conditions associated to this program are:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \delta^1} &= 0 \quad \frac{\phi}{(p_k^1 + \delta^1)p_k^{1\beta^1}} - \lambda = 0 \\ \frac{\partial \mathcal{L}}{\partial \delta^2} &= 0 \quad \frac{(1 - \phi)}{(p_k^2 + \delta^2)p_k^{2\beta^2}} - \lambda = 0 \\ \frac{\partial \mathcal{L}}{\partial G_h} &= 0 \quad \phi \frac{\ln(p_k^1)}{p_k^{1\beta^1}} \frac{\alpha_2^1}{G_h} + (1 - \phi) \frac{\ln(p_k^2)}{p_k^{2\beta^2}} \frac{\alpha_2^2}{G_h} - \lambda \frac{p_h}{S_h} = 0 \\ \frac{\partial \mathcal{L}}{\partial G_t} &= 0 \quad \phi \frac{\ln(p_k^1)}{p_k^{1\beta^1}} \frac{\alpha_3^1}{G_t} + (1 - \phi) \frac{\ln(p_k^2)}{p_k^{2\beta^2}} \frac{\alpha_3^2}{G_t} - \lambda \frac{p_t}{S_t} = 0 \\ \frac{\partial \mathcal{L}}{\partial \lambda} &= 0 \quad I - \delta^1 - \delta^2 - p_h \frac{G_h}{S_h} - p_t \frac{G_t}{S_t} = 0 \end{aligned}$$

Now, from these conditions we find an expression for δ^1 , δ^2 , G_h and G_t :

$$\delta^1 = \frac{\phi}{\lambda} \frac{1}{p_k^{1\beta^1}} - p_k^1 \quad (32)$$

$$\delta^2 = \frac{1 - \phi}{\lambda} \frac{1}{p_k^{2\beta^2}} - p_k^2 \quad (33)$$

$$G_h = \frac{1}{\lambda} \frac{S_h}{p_h} \left(\phi \frac{\ln(p_k^1)}{p_k^{1\beta^1}} \alpha_2^1 + (1 - \phi) \frac{\ln(p_k^2)}{p_k^{2\beta^2}} \alpha_2^2 \right) \quad (34)$$

$$G_t = \frac{1}{\lambda} \frac{S_t}{p_t} \left(\phi \frac{\ln(p_k^1)}{p_k^{1\beta^1}} \alpha_3^1 + (1 - \phi) \frac{\ln(p_k^2)}{p_k^{2\beta^2}} \alpha_3^2 \right) \quad (35)$$

We can now replace (32)-(35) into the budget constraint and find an expression for λ :

$$\lambda = \frac{1}{I} \left[\frac{\phi}{p_k^{1\beta^1}} \left(1 - p_k^{1\beta^1+1} - (\alpha_2^1 + \alpha_3^1) \ln(p_k^1) \right) + \frac{1 - \phi}{p_k^{2\beta^2}} \left(1 - p_k^{2\beta^2+1} - (\alpha_2^2 + \alpha_3^2) \ln(p_k^2) \right) \right] \quad (36)$$

We can now input (36) into (32)-(35) and find the solution to the first stage of the

maximization problem.

Furthermore, to obtain the demand for the private goods, we substitute the first stage functions into (28) and (29).

Finally, we choose a functional form for the pareto-weight. Following Blundell et al. (2005), we choose function proportional to the individual wages:

$$\phi = \frac{\theta w^1}{\theta w^1 + w^2} \quad (37)$$

We now have a system of equations for $k^1, k^2, c^1, c^2, \delta^1, \delta^2, G_t, G_h$ as functions of $p_k^1, p_k^2, p_t, p_h, I, Z,$ and S .

Due to lack of data on the efficiency of some energy services and prices, this model cannot be implemented to date.

C Data treatment

The data base from the Family Budget survey comes in 10 different subsets of data. These subsets of data are organized by type of expenditure:

Individual expenditures, household expenditures, expenditures children, telecommunications, insurances, private cars and on other vehicles (i.e. bike), durable goods, cultural goods, health, parking and holiday trips.

There is another subset of data including the expenditures documented in cards during a reference week.

Furthermore, there are three subsets of data on the individuals and household's socio-economic characteristics. Overall, these data gather over 3000 variables about household and individual characteristics, expenditures and related variables such as periodicity or quantities.

We did a significant work of data cleaning and formatting. First we did an inventory of the available variables and their definitions to determine how to compose each group of expenditure.

Moreover, we chose the expenditure variables of each dataset, coupled with variables regarding the periodicity and the quantities consumed. It is important to note that the variables regarding expenditures were declared for a different periodicity. For instance, individuals are inquired about expenditures on clothing over the last two months, while the periodicity of the expenditures on telecommunications is subject to the length of the subscriptions and it varies for every individual. An extensive work was required to standardized the periodicity of all variables.

Expenditures on fuel and first necessity goods, like food and drinks, were taken from the cards. Individual incurred in this kind of expenses on a regular basis, therefore is more accurate to take the weekly information and extrapolate it to the month.

We then classify the expenditures following the Classification of Individual Consumption

According to Purpose (COICOP) to facilitate the further aggregations. Furthermore, we classify and aggregate the variables according the model.

Finally, taxes, credits and expenditures on durable good were excluded from the analysis.

Chapter 3

When "green irrigation" increases carbon emissions

This chapter is based on a joint work with Catherine Benjamin. An early version will be published in *Revue économique* (forthcoming).

Parts of this chapter were presented at: the 6th Annual Conference of the French Association of Environmental and Resource Economists, Rennes, August 29-30, 2019; the 7th Annual Conference of the French Association of Environmental and Resource Economists, September 10-11, 2020.

Improving the efficiency of water use is usually presented as an opportunity for water conservation in the agricultural sector. Using more efficient irrigation systems should lead to agricultural yields, similar to those obtained initially, by using a smaller volumes of water (green irrigation). However, a more efficient irrigation system can paradoxically encourage agricultural producers to use more water. This effect is linked to the increase in the productivity of the production factor (rebound effect). One aspect largely overlooked is the impact of improved efficiency on energy demand. The aim of this chapter is to identify the factors that ensure the efficiency of green irrigation. Our contribution is to develop a model that takes into account the evolution of energy costs. Our results suggest that more efficient irrigation technologies result in an increase in water demand (rebound effect) and in energy demand. We find that even though efficiency improvements may contribute to water economies, this is achieved through a higher consumption on energy

which in turn contributes to CO₂ emissions. In other words, there seems to be a trade-off between water economies and CO₂ emissions reductions. Public decision-makers must therefore coordinate the objectives of environmental policies in water and energy, so that all policy objectives are achieved and not neutralized.

Keywords: Rebound effect, Agriculture, Water management, Investment aid.

1 Introduction

By 2050, global water demand is expected to increase by 55% according to a recent United Nations report (ONU, 2020). This report stresses the urgency of strengthening the resources devoted to water management. Industry needs are expected to increase by the latest forecast by 400%. As for the agricultural sector, experts say the current levels are not sustainable. Between 1961 and 2009, cultivated land expanded by 12%, while irrigated area increased by 117% (Banque Mondiale, 2016).

Water resources are at the heart of the climate changes observed in recent years. Globally, disparities in the distribution of water resources are likely to widen: episodes of drought are expected to be more frequent in regions already experiencing water shortages, while water availability is expected to increase in northern latitudes of the planet. These changes in the water cycle are likely to have major consequences for societies and ecosystems. Water resources will be threatened and affected in many countries, many regions, with impacts on all areas of development (access to water, food security, health, etc.). Moreover, the risks of disasters linked to water will increase, such as the modification of precipitation levels, accentuation of runoff linked to heavy precipitation and therefore the risk of erosion, and increase in sea level (IPCC, 2018; OCDE, 2014).

A particularly affected sector is the agricultural sector. Agriculture can both suffer from and contribute to water scarcity. Irrigation accounts for over 70% of global water use, over 44% on average for OECD countries and up to 95% in some developing countries (OCDE, 2014). The global consumption of water used for agriculture thus increased six-fold between 1900 and 2014 by accelerating the hydrological cycle (see Glossary), that is to say by increasing the levels of evaporation (IPCC, 2018).

Furthermore, water scarcity is expected to intensify as a result of climate change. For each degree of global warming, 7% of the global population will see a decrease of 20% or more in renewable water resources. Meanwhile, more frequent and severe droughts are affecting agricultural production and rising temperatures, which translates into increased

crop water demand. In addition to improvements in water-use efficiency and agricultural productivity, actions to harvest and reuse freshwater resources and increase the safe use of waste water are needed (Boretti and Rosa, 2019).

The increasing global demand for resources, such as water, has been met with a new wave of resource efficiency policies worldwide. In the European Union, a reference document on resource efficiency policy named *Roadmap to a Resource Efficient Europe* (2011), identifies potential measures to limit the current pressure on water use. One instrument put in place is the introduction of subsidies to encourage producers to invest in irrigation techniques that are more water-efficient. Improving the efficiency of water use is usually presented as an opportunity for large water savings in the agricultural sector. These methods that deliver water to crops more efficiently are called "green irrigation" (Gómez and Pérez-Blanco, 2015).

Investing in more efficient irrigation techniques should allow the farmer to achieve agricultural yields identical to those obtained initially but using a smaller volume of water. Some of the amount of water brought to crops with older material can be lost through evaporation without having been used (Pfeiffer and Lin, 2014a).

However, investments in more efficient irrigation systems do not always translate into reduced consumption.

The literature shows that improvements in efficiency may lead farmers to adapt their consumption behavior, which could have an unintended side effect of increasing water consumption. This behavioral adaptation is known in the economic literature as the rebound effect or the Jevons paradox. It has been the subject of much empirical work in the field of energy and transport (Sorrell et al., 2009). This paradox takes place mainly due to the reduction in the relative cost of water per unit of output, potentially accompanied by a reduction in the absolute price of water. Farmers using more efficient techniques may have an incentive to use more water, either by irrigating new agricultural areas or by cultivating water intensive crops, which would cancel out the efficiency gains (Berbel et al., 2015; Sears et al., 2018).

Moreover, the impact of efficiency improvements on the cost of irrigation is often overlooked in the literature. The cost of irrigation is made up of the water charges and the energy charges required to the operation of the irrigation equipment (usually electricity). More efficient irrigation systems require more energy to operate, leading to an increase in the demand for energy. This, in turn, will increase the overall irrigation cost. In this case, an improvement in irrigation efficiency can lead to a decrease in water demand through an increase in irrigation cost (and the demand for energy) (Sears et al., 2018).

As an example, in the south of Spain, a government policy for modernization of the irrigation systems in the early 2000's, made possible to reduce the demand for water per unit of irrigated area by more than 20% over 1950 levels. However, energy demand has increased by 149% over the same period (Rodríguez-Díaz et al., 2011). This aspect has been found in other countries such as the United States, Syria, India or Morocco (Belaud et al., 2020).

The aggregation of these effects, the rebound effect and the irrigation cost, leads to an ambiguous result in the policy. Improving irrigation efficiency increases water productivity and encourages farmers to consume more of the resource, contributing to water depletion and scarcity. The improvement in efficiency leads to an increase in energy demand, which increases the cost of irrigation and contributes to a decrease in water demand. This contributes to greenhouse gas emissions due to the use of energy from non-renewable sources (Belaud et al., 2020).

The aim of this chapter is to identify the factors that ensure the effectiveness of "green irrigation". We want to assess which factor between the efficiency improvement and the increase in energy costs have the most influence on the demand for water. To this effect, we investigate both theoretically and empirically the impact of a price shock on energy prices.

We present a model, based on Huffaker and Whittlesey (2003), which allows us to analyze the variation in irrigation water demand following an increase in the efficiency of the irrigation system. In this model, we define the cost of irrigation as a function of the price

of energy. Next, we do a static comparative analysis to determine under which conditions an improvement in efficiency leads to a decrease in water demand. This analysis shows that final impact of a technological improvement of the irrigation system, is determined by the energy costs, in our model represented by the price of energy. Then, we simulate the theoretical model in order to assess the final impact of the policy. In this exercise we simulate a price shock on energy prices and analyze the impact of this on water demand. Finally, we implement an empirical model to test the theoretical findings. We approximate the farmer's production function by a translog function and we estimate the effect of a price shock on demand for water, depending on the type of irrigation system used by the farmers.

The contribution of this chapter is twofold. We contribute to the literature from a theoretical perspective by modeling the cost of irrigation such that we can take into account the effect of energy prices on the demand for water. We show that the success of water conservation policies is tightly linked to the evolution of energy charges. Furthermore, that it may also depend on fluctuations in the price of energy and can vary widely depending on economic conditions.

We contribute from an empirical perspective by implementing a methodology that allows us to test the combined impact on the demand for water of an improvement in irrigation efficiency and the increase in energy costs. The identification of the cost effect relies on the variation of energy prices during the price shock that followed the 2008 crisis. We argue that farmers will react similarly to an energy price shock than to an increase of energy costs after an efficiency improvement.

We show that even though an efficiency improvement may contribute to water economies, it leads to a higher consumption on energy which in turn contributes to CO₂ emissions. In other words, there seems to be a trade-off between water economies and CO₂ emissions reductions.

The remaining of this chapter is organized as follows. The next section presents a review of the literature on the policy impacts of improving the irrigation efficiency. The third

section proposes a microeconomic model of irrigation demand. The following section presents a simulation of the theoretical model and draws some policy implications. The next three sections present the empirical strategy, the data and the results. The final section concludes.

2 Improving irrigation efficiency

The adoption of new and more efficient irrigation practices has often been a leading public policy in many countries, notably through investment grants. However, these efficient technologies do not systematically lead to reductions in water use. (Menet et al., 2018; Sears et al., 2018).

After having defined the concept of irrigation efficiency, we provide a synthesis of the existing literature measuring the effects of investment subsidy programs on water consumption. We present results of both theoretical and empirical work.

2.1 What is an efficient irrigation system?

The irrigation technology efficiency is noted ε . This parameter is defined by the ratio between the crop water needs or need for evapotranspiration, noted ET , and the quantity of water supplied, noted W (Cornish et al., 2004):

$$\varepsilon = \frac{ET}{W} \quad (1)$$

Crops water requirements depend on several factors, intrinsic or extrinsic to the type of crop (species, variety) and related to its environment, such as stage of vegetation, soil moisture, climatological conditions (precipitation, insolation, wind).

Take for instance the theoretical case of a perfectly efficient technology. It means that the volume of water supplied to the crop is exactly the quantity it needs. In this case $\varepsilon = 1$.

In practice, there is no irrigation technology that achieves a perfect level of efficiency, in other words, ε is less than 1 (Huffaker and Whittlesey, 2003).

Each technology is characterized by a specific level of efficiency. For example, sprinkler irrigation¹ has an average efficiency of 65%. A subsurface drip² irrigation system has an average efficiency of 90%. The latter technique is more efficient because infiltration of water and runoff are lower than in sprinkler irrigation (Barta et al., 2004).

2.2 Impact of green irrigation on the demand for water

Several studies show that the impact of an improvement in the efficiency of the irrigation system on water consumption depends on three effects: (1) the technical effect, (2) the productivity effect and (3) the cost effect. These three effects have different impacts on water consumption (Berbel et al., 2015; Gómez and Pérez-Blanco, 2015).

The first effect, the technical effect, decreases water consumption. All other things being equal, the amount of water used in irrigation decreases by the same percentage as the improvement in efficiency. Suppose an agricultural producer who adopts a new technology that improves efficiency by 25%, the expected water savings are then 25%.³ Thus, this first effect reduces water consumption.

This is the underlying principle behind a large number of irrigation water management policies. However, this reasoning does not take into account the fact that farmers can adapt their behavior, from which other effects may arise. Studies on the rebound effect in the energy field observe that this technical effect creates an income effect, since all other things being equal, an increase in efficiency allows the farmer to achieve additional income through the water saved (Sorrell et al., 2009).

The second effect, the productivity effect, arises from the fact that water productivity

¹Surface irrigation method characterized by the free flow of water through a network of canals that can cover up to half of the surface (Barta et al., 2004).

²A micro-irrigation method of delivering water directly to or into the soil (Barta et al., 2004).

³For instance, switching from sprinkler irrigation, with an average efficiency level of 65%, to subsurface drip irrigation, with an average efficiency level of 90%, corresponds to an improvement of 25%. As a result, the expected water savings are then 25%.

increases as a result of water being applied in a more efficient way. For the same amount of water applied more efficiently, the crop yield will be higher, which is an incentive to use more water. This effect may offset the technical effect and overall lead to the use of larger volumes of the resource. In the literature, the productivity effect is equated with the rebound effect or the Jevons paradox (Gómez and Pérez-Blanco, 2015; Sears et al., 2018). This productivity effect therefore increases water consumption.

Finally, the third effect corresponds to the variation in the cost of irrigation coming from a more intensive use of energy of more efficient technologies. The cost of irrigation is mainly made up of the cost of water and the cost of the energy needed to operate the irrigation equipment (usually electricity). More efficient irrigation systems require more energy to operate, leading to an increase in the demand for energy. This, in turn, will increase the overall irrigation cost (Belaud et al., 2020). This effect can lead to a decrease in water demand (Gómez and Pérez-Blanco, 2015).

The aggregation of all these effects defines the net effect of improved efficiency on water consumption. Depending on the importance of the productivity effect and the cost effect, the water savings achieved through the use of more efficient irrigation technologies will be greater or lesser. The real impact of water resource conservation policies may be overestimated when the interaction of these effects is not analyzed.

2.3 Evidence of the rebound effect in the literature

Applied work on the subject of water rebound effects is recent. Most of the work are ex-post evaluations assessing the impact of investment subsidy programs on water consumption. Empirical results show that these programs have ambiguous effects on water use and do not systematically reduce water demand (Lin Lawell, 2016).

Table 1 summarizes the main characteristics and results of empirical studies. The majority of applied works use panel data on farms.

Empirical results show that in some cases, public water conservation programs have led to increased water use. For instance, in China, the efficiency of irrigation systems has

Table 1: Empirical research on the rebound effect and the use of energy in irrigation

| Authors | Period | Region | Results |
|----------------------------------|---------------------------------------|---------------|--|
| Peterson and Ding (2005) | 1985-2000 | United States | No rebound. Only corn crops. |
| Ward and Pulido-Velazquez (2008) | 2006 - 2025 ^a | United States | Rebound effect if subsidies or in absence of regulations. |
| Pfeiffer and Lin (2014a) | 1996-2005 | United States | 1–2.5% increase of applied water. Rebound effect >100%. |
| Pfeiffer and Lin (2014b) | 1996-2014 | United States | Energy price elasticity of demand for water: -0.26 |
| Rodríguez-Díaz et al. (2011) | 1996-2002 ; | Spain | ↓ Water demand (23%). |
| Fernández García et al. (2014) | 2010-2012 ^b | | ↑ Energy charges (149%) ↑ Irrigation total cost (52%). |
| Berbel et al. (2015) | 1999-2001 ; 2009-2011 ^b | Spain | Rebound effect in absence of regulations. |
| Song et al. (2018) | 1998–2014 ^c | China | Rebound effect of 61.49% |
| Li and Zhao (2018) | 1991 - 2010 | United States | Rebound effect. ↑ Irrigated surface & water intensive crops. |

^a Simulation.

^b Comparative analysis, before and after efficiency improvement.

^c Aggregated data.

increased steadily over the past two decades. However, the volume of water withdrawn did not decrease as expected (Song et al., 2018).

This unexpected outcome is mainly the result of the productivity effect. If the productivity effect is high enough, access to more efficient irrigation technology would encourage farmers to adjust the type of crop, favoring crops with higher water requirements, as well as to increase the irrigated area (Li and Zhao, 2018; Pfeiffer and Lin, 2014a). In addition, if the demand for water is elastic and if the new technology increases agricultural yield, the volume of water used will increase (Huffaker and Whittlesey, 2003; Ward and Pulido-Velazquez, 2008).

On the other hand, some studies do not find a rebound effect in irrigation water (Peterson and Ding, 2005). They show that the existence of the rebound effect depends on the implementation of restrictive regulations on the use of water and the cultivated land (Berbel and Mateos, 2014; Berbel et al., 2015).

The ambiguity of these results can be explained by the interaction of effects explained

in the previous section. Several studies measuring the impact of an improvement in irrigation efficiency, consider the cost of irrigation as constant. For example, Li and Zhao (2018) focuses on the adoption of low energy-intensive irrigation technologies (LEPA - Low Energy Precise Application). The cost effect is then negligible and the improvement of the irrigation system leads to a rebound effect. In other situations, granting subsidies to farmers would offset the cost effect, which also leads to a rebound effect (Pfeiffer and Lin, 2014a; Ward and Pulido-Velazquez, 2008).

In practice, modernizing the irrigation system can lead to higher variable costs. This is because the use of a more efficient irrigation system leads to a more intensive use of energy. Thus, water demand may decrease due to the higher energy costs that drive up the total cost of water extraction. The share of energy in farmers' costs can range from 40% to 65%. In some cases, the importance of energy in the cost of irrigation leads farmers to reduce their water consumption even below the water levels required by the crop, which endangers agricultural yields (Rodríguez-Díaz et al., 2011). Espinosa-Tasón et al. (2020) estimate that in the period 2005-2013, irrigation efficiency increases by 0.4% and energy consumption per m³ increases by 2.2%. Between 2014 and 2017, the same indicators increase by 0.3% and 4.5%, respectively. Similar results are found for France and Australia (see appendix A).

In conclusion, water economies can be observed as a result of the efficiency improvement or due to the higher energy costs. The overall impact of efficiency improvement on water conservation depends on the size of the productivity and the cost effect. This implies that water conservation may be achieved at the expense of higher GHG emissions coming from the increase in energy demand. Therefore, the energy issue cannot be excluded from the debate on efficient irrigation in agriculture (for more details see Belaud et al., 2020; Berbel et al., 2015).

3 Modeling of irrigation water demand

In this section, we present the basic theoretical model for irrigation water demand, based on the model proposed by Huffaker and Whittlesey (2003). The aim is to estimate theoretically the net effect of an improvement in the irrigation system, in other words, to take into account the productivity effect, the income effect (both at the source of the rebound effect) and the cost effect (linked to the use of energy).

In this model, we define the cost of irrigation as a function of the price of energy. For a given level of efficiency, a rise in the price of energy raises the prices of energy-intensive factors of production, such as the irrigation. Consequently, the farmer will react to an increase in the price of energy in the same way he would react to an improvement in efficiency, namely by reducing the demand for the water resource (Pfeiffer and Lin, 2014b; Zilberman et al., 2008).

Our contribution is to link the cost of irrigation to the price of energy. This extension allows us to further understand to what extent water demand decisions depend on the economic context, here represented by the price of energy.

3.1 Water demand and components of the irrigation price

The farmer's production function depends on two production factors, water and irrigation technology, here represented by the level of efficiency ε . The efficiency of the irrigation system is the percentage of the total amount of water supplied that meets the crop's water needs, in other words $\varepsilon \in (0, 1)$ (Equation (1)).

Each unit of water supplied to the crop will be used to satisfy its transpiration capacity or evapotranspiration (ET) demand. Water consumption, denoted by W , is determined by the crop's water requirements and the level of efficiency of the irrigation system.

The unit cost of water irrigation is noted $C_w(\varepsilon, p_e)$. This cost includes water charges and energy charges required for the operation of the irrigation system, these are embedded in the irrigation technology ε . Additionally, all things being equal, the cost of water

irrigation will be affected by the fluctuations in energy prices, noted p_e , on account of the energy requirements inherent to the irrigation technology. Finally, the cost of water irrigation would also include the cost of labor, but, for the sake of simplicity, we assume that it is constant. We assume that $\partial C_w(\varepsilon, p_e)/\partial \varepsilon < 0$ and $\partial C_w(\varepsilon, p_e)/\partial p_e > 0$.

3.2 Optimization program

The farmer optimizes his water demand W , for a given level of irrigation efficiency, so as to maximize his short-term profit, constrained by the cost of irrigation.

We denote $Y = Y(W, \varepsilon)$ the farmer's production function. Y is concave with respect to the level of water supplied, W , and the efficiency of the irrigation system, ε . P is the price of the agricultural product. We assume that the production function admits constant returns.

For a given the level of efficiency ε , the farmer chooses the level of irrigation water $W(\varepsilon)$ that maximizes his profit. The optimization program is written:

$$\max_W \pi = \max_W PY(W(\varepsilon), \varepsilon) - C_w(\varepsilon, p_e)W(\varepsilon) \quad (2)$$

The first order necessary condition (CPO) for the (2) program is:

$$\frac{\partial \pi}{\partial W} = P \frac{\partial Y(W(\varepsilon), \varepsilon)}{\partial W} - C_w(\varepsilon, p_e) = 0 \quad (3)$$

The farmer's optimal water demand function is given by: $W^*(P, \varepsilon, C_w(\varepsilon, p_e))$.

Impact of an efficiency improvement on water demand

In order to measure the rebound effect, we start by calculating the total derivative of the Equation (3) with respect to ε , from which we find that:

$$\frac{\partial W}{\partial \varepsilon} = -\frac{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial \varepsilon \partial W} \quad (+/-)}{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2} \quad (-)} + \frac{\frac{\partial C_W(\varepsilon, p_e)}{\partial \varepsilon} \quad (-)}{P \frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2} \quad (-)} \quad (4)$$

The change in demand following an improvement in efficiency is made up of two terms. The first term corresponds to the productivity effect. The sign of this effect depends on the cross derivative between efficiency and water consumption (the numerator of the first term of the Equation (4)).

Gómez and Pérez-Blanco (2015) suggest that improving efficiency increases water productivity ($\partial^2 Y / \partial \varepsilon \partial W > 0$). In which case, a policy encouraging increased efficiency leads to an increase in the demand for irrigation water. Empirical evidence suggests that a more efficient irrigation can indeed increase farmers' unit yields (Pfeiffer and Lin, 2014a; Ward and Pulido-Velazquez, 2008). If, on the contrary, improving efficiency decreases water productivity ($\partial^2 Y / \partial \varepsilon \partial W < 0$), the policy leads to a decrease in water demand.

The second term corresponds to the income effect which results from the technical effect (see part 2.2): all other things being equal, a more efficient irrigation system makes it possible to reduce the quantity of irrigated water, which represents savings for the farmer. The sign of this effect is positive and it is at the origin of the rebound effect illustrated in the energy literature (Sorrell et al., 2009).

In the next section, we analyze how the relation $\partial W / \partial \varepsilon$ adjusts to a change in energy costs. In this framework, the energy costs are represented by the energy prices. Therefore, a changes in the energy costs would be approximate by a shock on the price of energy.

4 Policy simulation: Water economies after a price shock

In this section, we discussed the results induced by the model presented in the 3.2 part. The leading hypothesis of this section is that farmers react similarly to an energy price shock and to an improvement in efficiency. Due to the fact that these two shocks result in an increase in energy charges. Here, we analyze the effect of a price shock.

The cost effect (related to the increase in energy charges contained in the efficiency ε) is found by calculating the total derivative of the FOC (Equation (3)) with respect to the energy price. Using the implicit function theorem we can write the demand for water as a function of the price of energy, $W^*(p_e)$, which allows us to find the following derivative:

$$\frac{\partial W}{\partial p_e} = \frac{\frac{\partial C_w}{\partial p_e}}{P \frac{\partial^2 Y}{\partial W^2}} \quad (5)$$

Equation (5) represents the variation in water demand induced by an increase in the price of energy. This effect is negative.

To analyze the combined effect of an improvement in the irrigation technology and the cost effect associated to it, we do a simulation exercise by using some particular parametric form for the production function.

We estimate the variation in water demand following an efficiency improvement, given by (4). Furthermore, we see how it changes when faced to a shock on the price of energy.

The reminder of this section presents the main assumptions of the simulation, the model calibration and the results.

Assumptions

We represent the farmer's production function by a simple parametric form. We then create the profit maximization program and find the respective demand for water.

Afterwards, we estimate Equation (4), which gives us the variation of the demand for water after an improvement in the irrigation efficiency.

The production function is defined as a Cobb-Douglas function:

$$Y(W(\varepsilon), \varepsilon) = \varepsilon^\alpha W^\beta \quad (6)$$

Where α and β are the elasticities of the production function.

The cost of water irrigation per unit is given by:

$$C_w(\varepsilon, p_e) = \gamma_0 + \gamma_1 \varepsilon + \gamma_2 p_e \quad (7)$$

Where γ_0 , γ_1 and γ_2 are the parameters of the cost function.

The profit maximization program is defined as:

$$\pi = P \varepsilon^\alpha W^\beta - (\gamma_0 + \gamma_1 \varepsilon + \gamma_2 p_e) W \quad (8)$$

Therefore, from (8), the first order necessary condition (CPO) are given by:

$$\frac{\partial \pi}{\partial W} = 0 \quad (9)$$

$$P\beta w^{\beta-1} \varepsilon^\alpha - (\gamma_0 + \gamma_1\varepsilon + \gamma_2p_e) = 0$$

Under this setting, the demand for water is given by:

$$W^* = \left(\frac{\gamma_0 + \gamma_1\varepsilon + \gamma_2p_e}{P\beta\varepsilon^\alpha} \right)^{\frac{1}{\beta-1}} \quad (10)$$

And the optimal production function, for a given level of ε is given by :

$$Y(W(\varepsilon), \varepsilon) = \varepsilon^\alpha \left(\frac{\gamma_0 + \gamma_1\varepsilon + \gamma_2p_e}{P\beta\varepsilon^\alpha} \right)^{\frac{\beta}{\beta-1}} \quad (11)$$

The effect of an improvement in the irrigation efficiency on the demand for water is defined by:

$$\frac{\partial W}{\partial \varepsilon} = \frac{\left(\frac{\gamma_0 + \gamma_1\varepsilon + \gamma_2p_e}{P\beta\varepsilon^\alpha} \right)^{\frac{\beta}{\beta-1}} \left(\frac{\alpha(\gamma_0 + \gamma_1\varepsilon + \gamma_2p_e)}{P\beta\varepsilon^{\alpha+1}} - \frac{\gamma_1}{P\beta\varepsilon^\alpha} \right)}{\beta-1} \quad (12)$$

However, as we saw in the previous section, $\partial W/\partial \varepsilon$ can be decomposed in two terms. The productivity effect and the income effect. Therefore, we compute separately those terms. We find that the productivity effect is:

$$\frac{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial \varepsilon \partial W}}{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2}} = \frac{\alpha W^*}{(1 - \beta)\varepsilon} \quad (13)$$

Finally, the income effect is given by:

$$\frac{\frac{\partial C_W(\varepsilon, p_e)}{\partial \varepsilon}}{P \frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2}} = \frac{\gamma_1 W^{*2-\beta}}{(1 - \beta)\beta \varepsilon^\alpha} \quad (14)$$

Where W^* is the optimal water demand (11).

Model calibration

Now, we calibrate the equations for the productivity and income effects and compare two different scenarios regarding energy prices.

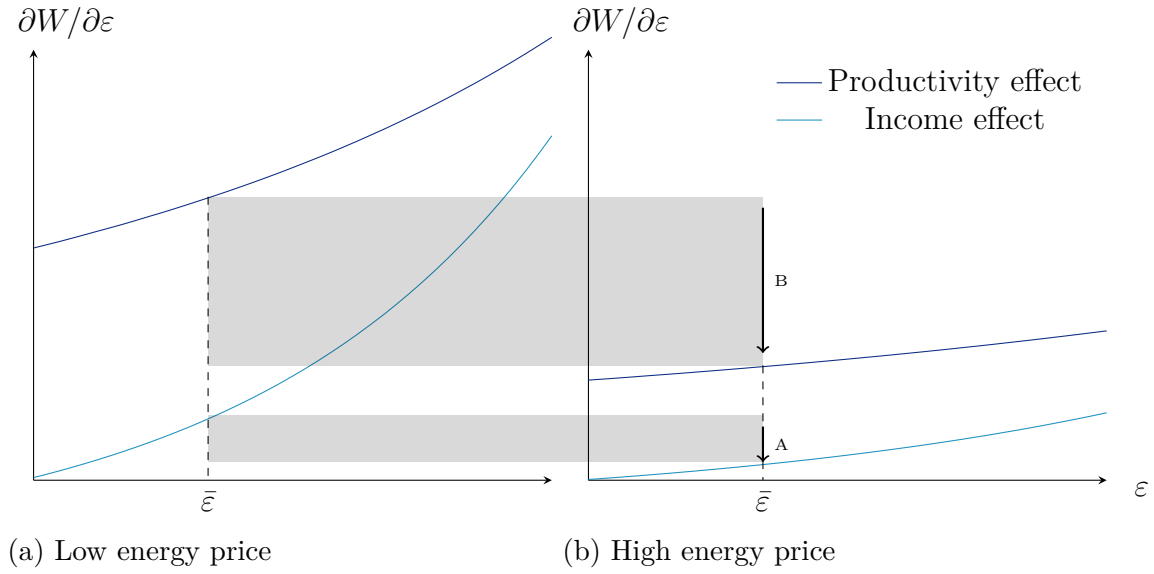
The first scenario, is characterized by low energy prices, under this setting $p_e = 0.25$. The second scenario, is characterized by high energy prices, under this setting $p_e = 0.9$.

The other parameters of the model were normalized between zero and one, as to have continuous functions.

The elasticities of substitution in the production function, α and β were fixed at 0.5. The food prices P were fixed at 1. The parameter of the cost function γ_0, γ_1 and γ_2 were fixed at 1, 1 and 0.35 respectively.

The simulation was run using the software `Wolfram Mathematica`. The results of this exercise are discussed in the following section.

Figure 1: Impact of an energy price shock on water demand



Simulation results

The figure 1 illustrates the interaction of the three effects described in Equations (17) and (18): the productivity and income effects with a low energy price (Figure 1a) and a high energy price (Figure 1b).

In a situation of low energy prices, the productivity effect is positive and decreasing up to the efficiency level $\bar{\varepsilon}$, after which it becomes constant. The income effect is still increasing.

At a given level of efficiency, a shock on the energy price makes possible a reduction in demand for water by $(A + B)$ (Figure 1b). However, the rebound effect remains positive. Thus, the demand for water increases with the efficiency levels but this progression is slowed down in the presence of a shock on the price of energy.

These results suggest that the water savings achieved with the modernization of irrigation systems have not been achieved due to technological improvement. The decrease in water use is rather due to the increase in energy charges.

If we then consider a subsidy policy per unit of water, denoted $S(\varepsilon)$, a new positive term: $S(\varepsilon)W(\varepsilon)$ will be added to the optimization program (2). The first order conditions (3)

would also be modified accordingly. Finally, an additional term will be added to the Equation (4):

$$\frac{\partial W}{\partial \varepsilon} = -\frac{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial \varepsilon \partial W}}{\frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2}} + \frac{\frac{\partial C_W(\varepsilon, p_e)}{\partial \varepsilon}}{P \frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2}} - \frac{\frac{\partial S(\varepsilon)}{\partial \varepsilon}}{P \frac{\partial^2 Y(W(\varepsilon), \varepsilon)}{\partial W^2}} \quad (4')$$

This new term is positive. This implies that subsidies, whether for the adoption of technologies or for energy costs, will further strengthen the rebound effect. They compensate for increased energy charges and allow the farmer to increase the demand for water. This result does not mean that subsidies should be avoided. It points out that policymakers must ensure that subsidies do not lead to a trade-off between water savings and energy savings.

5 Empirical strategy

In this section we test empirically the model presented above using data from the Farm Accountancy Data Network (FADN) in France, from 2006 to 2011. The identification of the water demand relies on the duality theory to represent the farmer's technology by the cost function (Chambers and Just, 1989). With this strategy, we attempt to explain the variation in farmers expenses using pooled cross-sectional data on production, prices, irrigation technology and surface for the period 2006-2011.

Here, we focus on expenses on water and energy and their interdependencies. To this effect, we approximate the farmer's production function by a translog function and we estimate the demand for water.

Furthermore, we test the combined impact on the demand for water of an improvement in irrigation efficiency and the increase in energy costs. The identification of the cost effect relies on the variation of energy prices during the price shock that followed the 2008 crisis. We argue that farmers will react similarly to an energy price shock than to an increase of

energy costs after an efficiency improvement. We estimate the impact of the price shock by controlling for different irrigation technologies.

The remainder of this section presents the empirical strategy for the estimation of the rebound effect and the cost effect. Notice that, farmer's decision process consists of a choice of irrigation technology and, subsequently, the level of demand for water. This chapter focuses on the second part, that is to say, understanding the demand for water once the irrigation technology has been chosen. The results presented can shed some light on the existence of water rebound effects and the nexus water-energy. However, they cannot predict technology choices.

5.1 Economic Modeling

We rely on the duality theory to represent the farmer's technology by the variable cost function. In the short run, capital (for instance, irrigation efficiency) and land are fixed. The farmer chooses the level of irrigation water, which in combination with a given irrigation technology, will determine the level of energy. The variable costs are defined by:

$$VC(p, Y; s, x) = \left\{ \min_x \sum_j p_j q_j \mid q \in V(Y), w > 0 \right\} \quad (15)$$

Where q is the vector of variable inputs, water w and energy e , ($j = 1, 2$) and the respective prices $p = \{p_w, p_e\}$, Y is the vector of output and $V(Y)$ the production technology, s is a vector of production shifters such as the characteristics of the irrigation and x is a vector of other variables affecting the farm-level costs.

Including s as an argument implies that, for a given output level, the choice of inputs can be affected by the irrigation characteristics, such as the efficiency levels or the energy intensity.

Shephard's Lemma states that the derivative of the cost function (15) with respect to the

price of input j is equal to the demand of input j . This demand function is equal to the cost share of input j , defined as:

$$\omega_j = \frac{\partial VC(p, Y; s, x)}{\partial p_j} = \frac{p_j q_j}{VC} = q_j \quad (16)$$

ω is the vector of cost shares for these inputs. These cost shares represent the cost-minimizing demands.

This cost function is assumed to be concave on p , non-decreasing in p and Y and homogeneous of degree one with respect to p . A set of constraints must be set on $VC(p, Y; s, x)$ in order to assure that it meets these conditions.

5.2 Identification of the Cost Effect

We want to evaluate how farmer's demand for water, under different irrigation technologies, responds to an increase in energy costs. In other words, we want to estimate the cost effect. We argue that farmers will react similarly to an energy price shock than to an increase of energy costs after an efficiency improvement. Therefore, we identify the cost effect through the effect of the price shock that followed the 2008 crisis. To do so, we include interactions between a time variable and the type of irrigation (collective or individual) used by the farmer.

The variable *time* accounts for the price shock after 2008. The *irrigation* variable categorizes farmers the type of irrigation: collective or private (individual).

The farmers attached to a collective irrigation network constitute the reference group. In a collective irrigation system, the infrastructure needed for the transport of the water and its storage benefits several farms. These collective structures may be privately owned, for instance by a private firm or an agricultural cooperative, or may be a public property, for instance, a certified union associations (ASA⁴) or Regional Development Companies

⁴Associations Syndicales Autorisées.

(SAR⁵) (Garin et al., 2013).

Collective irrigation systems tend to be older and therefore less energy consuming, meaning that they will be less affected by a shock on energy prices. Furthermore, these systems were developed collectively usually because they required a sizable investment, meaning that they do not renew their systems (i.e. efficiency) frequently (Garin et al., 2013). These characteristics made this group a good reference point for water demand after a price shock.

In a private (individual) irrigation system, the infrastructures needed for water transport and storage (i.e. the pump, reservoir, drip or well) are used only by one farm. Farms require a pumping system to transport the water from the source to the crops. The amount of energy required to irrigate the crops is mainly determined by the the distance from the source to the plot. In the last decades, technological progress has made accessible new and more efficient irrigation pumps to individual farmers. These new devices allow farmers to extract water from rivers or aquifers several dozens of meters below ground level (Garin et al., 2013).

This group can be then categorize depending on the source of the irrigation water: *Hill reservoir*, *Drip or well* and *River pumping*. Each of these irrigation sources has distinct properties (i.e. depth, distance to plot, elevation). Therefore, the efficiency of application and the energy needs may differ.

5.3 Model Specification

The variable cost function at the farm level is approximated by the a translog function. This functional form is flexible and satisfies price homogeneity assumptions by imposing linear restrictions on the parameters (Chambers and Just, 1989).

The short-run variable cost of the farm is defined by the following translog cost function:

⁵Sociétés d'Aménagement Régionales.

$$\begin{aligned}
\ln VC_i = & \alpha_0 + \alpha_w \ln p_{w,i} + \alpha_e \ln p_{e,i} + \alpha_y \ln Y_i + \frac{1}{2} \left(\beta_{ww} \ln p_{w,i}^2 + \beta_{ee} \ln p_{e,i}^2 + \beta_{yy} \ln Y_i^2 \right) \\
& + \beta_{we} \ln p_{w,i} \ln p_{e,i} + \beta_{wy} \ln p_{w,i} \ln Y_i + \beta_{ey} \ln p_{e,i} \ln Y_i + \beta_{wT} \ln p_{w,i} D_T \\
& + \beta_{eT} \ln p_{e,i} D_T + \beta_{yT} \ln Y_i D_T + \sum_k \beta_{wG}^k \ln p_{w,i} D_G^k + \sum_k \beta_{eG}^k \ln p_{e,i} D_G^k \\
& + \sum_k \beta_{yG}^k \ln Y_i D_G^k + \sum_k \beta_{wTG}^k \ln p_{w,i} D_T D_G^k + \sum_k \beta_{eTG}^k \ln p_{e,i} D_T D_G^k \\
& + \sum_k \beta_{yTG}^k \ln Y_i D_T D_G^k + \alpha_T D_T + \sum_k \alpha_G^k D_G^k + \sum_k \alpha_{TG}^k D_T D_G^k + \sum x_i + \epsilon_i \quad (17)
\end{aligned}$$

The variable cost equation includes the logarithms of each input price, $p_{w,i}$ and $p_{e,i}$, and output Y_i for the farm i , their squared terms and their cross-products. Subscripts w and e represent inputs water and energy respectively.

The model includes a set of dummy variables, and their interaction with prices and output. D_T is the time variable taking the value of 0 before the price shock, marked at 2008, and 0 otherwise. D_G^k is the variable representing the type (and source) of irrigation k (with $k = 1, 2, 3$).

In the irrigation variable, the reference group includes farmers attached to the collective irrigation system. The other groups include farmers attached to an individual irrigation system and are categorized as: *Hill reservoir* ($D_G^1 = 1, D_G^2 = D_G^3 = 0$), *Drip or well* ($D_G^2 = 1, D_G^1 = D_G^3 = 0$) and *River pumping* ($D_G^3 = 1, D_G^1 = D_G^2 = 0$). $D_T D_G^k$ corresponds to the interaction between the time and irrigation variables.

The vector of exogenous variables x includes fixed effects by techno-economic orientation (OTEX) to control for differences in technology specific to a given economic orientation and a variables for investment subsidies granted to farms. Finally, ϵ_i is the error term with the usual properties.

From Shepard's Lemma, the cost shares $\omega_{j,it}$ of the two inputs can be expressed as elasticities of the cost function (17) with respect of the input prices. These are defined as:

$$\begin{aligned} \omega_{j,it} = & \alpha_j + \beta_{jj} \ln p_{w,it} + \beta_{jj'} \ln p_{e,it} + \beta_{jy} \ln Y_{it} + \\ & \beta_{jT} D_T + \sum_k \beta_{jG}^k D_G^k + \sum_k \beta_{jTG}^k D_T D_G^k \end{aligned} \quad (18)$$

Where $j \neq j'$ and $j, j' \in \{w, e\}$. Furthermore, a set of constraints must be imposed the system. The *symmetry* condition implies that:

$$\beta_{jj'} = \beta_{j'j},$$

and the *homogeneity* condition impose that:

$$\begin{aligned} \sum_j \alpha_j = 1 & \quad \sum_j \beta_{jj'} = 0 & \quad \sum_j \beta_{jy} = 0 \\ \sum_j \beta_{jT} = 0 & \quad \sum_j \beta_{jG}^k = 0 & \quad \sum_j \beta_{jTG}^k = 0 \end{aligned}$$

for $j \neq j'$ and $j, j' \in \{w, e\}$.

We estimate the system formed by Equations (17) and only one of the cost shares in (18), otherwise the residual covariance matrix would be rank deficient. By the adding-up conditions, there is no need to estimate all cost shares, because their sum equals one, and consistent estimates can be drawn by excluding any one the share costs. Here we estimate the cost share for water. We use the iterated seemingly unrelated regression (SUR) method, which ensures that the resulting estimates are not sensitive to the choice of cost share (Baum and Linz, 2009).

The cost effect is represented by the coefficients β_{jTG}^k . These coefficients tell us if the effect of a price shock in water demand is significantly different for farms in the reference group and the other farms. In other words, these coefficients indicate if there is a significant cost effect that may induce farmers to reduce their demand for water.

We argue that farms using individual irrigation systems have access to more efficient and more energy intensive irrigation systems, whereas farms in the attached to the collective network use irrigation technologies that are less energy intensive. If these coefficients are not significantly different from zero, it means that the price shock affects everyone equally,

and therefore, water economies can be mainly attributed to improvements in irrigation technologies.

The lead hypothesis of this chapter is that these coefficients will be negative. Meaning that water economies are not only due to improvements in irrigation efficiency, but also due to the higher energy charges that come with these new technologies.

6 Data and summary statistics

The main dataset used in this empirical analysis comes from the Farm Accountancy Data Network (FADN) 2006-2011. Furthermore, we build a second dataset on input prices, coming from a variety of sources.

The FADN⁶ is a survey carried out in the Member States of the European Union. It monitors farms' income and business activities. Every year it collects accountancy data from about 80 000 agricultural holdings in the EU 27. The FADN is the only source of micro-economic data that is harmonised (the bookkeeping principles are the same in all Member States) and is representative of the commercial agricultural holdings in the Union.

The collected information is a valuable asset to draw up economic diagnoses and to simulate and understand the impact of public policies, for instance the impact of the measures taken under the common agricultural policy.

The FADN data collection is made by the Liaison Agencies of each state member, often together with agricultural research institutes. In France, this task is undertaken by the Office of Statistics and forecasting (SSP for its French name, Service de la Statistique et de la Prospective), a dependency of the French Ministry of Agriculture and Food.

Every year, 300 data entries are collected. These include data about surface and livestock structure, workforce, age of the farm manager. Information about the economic results production, intermediate consumption, added value, gross operating surplus, recurring

⁶European Commission - Farm accountancy data network.

income before income tax, and fixed asset balance sheet items (land, equipment, breeding animals), current assets, capital, debts, charges.

Around 7000 units are surveyed in metropolitan France and 300 overseas. The statistical unit are medium or large farms (Standard Gross Product greater or equal to 25 000 €). They use quota sampling, stratified by region, size and techno-economic orientation (OTEX).

The second dataset use gathers variables on prices of inputs water and energy. This data was collected from different sources, such as water agencies and the Ministry for Ecological and Social Transition (MTES).

The sample used in this work gathers farmers that have irrigated on a given year. We consider farmers attached to a public collective irrigation network or having a private irrigation system. We exclude farmers using both collective and private systems (mixed) to avoid confounding effects. The final sample have 7906 observations over the period 2006 to 2011, distributed in 3900 farmers in the collective network (reference) and a total of 4006 farmers using individual irrigation.

6.1 Data treatment and Variables of interest

The total variable cost (called variable cost, henceforth) is defined as the sum of the irrigation water and energy charges per farm. The respective cost shares are the ratio between those charges and total cost.

We use results from previous studies on irrigation prices in France (Bonnet, 2013⁷; Jourdan et al. 2018; Oosterhuis 2016) to compute the irrigation price for our sample. We estimate the price of the m³ of irrigation water by type of irrigation structure (collective or private) and type of water source.

Energy prices, mainly electricity, were estimated by using data on the Tax on the Final Electricity Consumption (TCFE). We compute an index based on the tax rate for the department and the commune. All variables were adjusted for inflation.

⁷As reported in the site Terre-net.fr.

Table 2: Summary statistics by type of irrigation system

| | <i>Collective irrigation</i> | | <i>Individual Irrigation</i> | | t-test |
|--|------------------------------|-------------------|------------------------------|-------------------|----------|
| | Mean (Min) | SD (Max) | Mean (Min) | SD (Max) | |
| Water charges | 3982 (0.00) | 5668 (64396) | 72.67 (0.00) | 258.5 (3363) | 2358*** |
| – Share of VC | 0.61 (0.00) | 0.29 (1.00) | 0.03 (0.00) | 0.08 (1.00) | 0.62*** |
| Energy charges | 2245 (0.00) | 3134 (36088) | 3784 (0.00) | 4812 (56093) | -1221*** |
| – Share of VC | 0.39 (0.00) | 0.29 (1.00) | 0.97 (0.00) | 0.08 (1.00) | -0.62*** |
| Irrigation Water Price (m ³) | 0.15 (0.15) | 0.00 (0.15) | 0.08 (0.05) | 0.05 (0.20) | 0.09*** |
| Energy Price | 76 (67.9) | 1.72 (78.5) | 75.68 (67.9) | 2.83 (78.5) | 0.7 |
| Investment subsidies | 13769 (0.00) | 30664 (347246) | 11884 (0.00) | 29725 (337628) | 0.00*** |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. Minimal and maximal values in parenthesis.

Note: descriptive statistics are computed on the year 2008. Constant values and prices. Units: €.

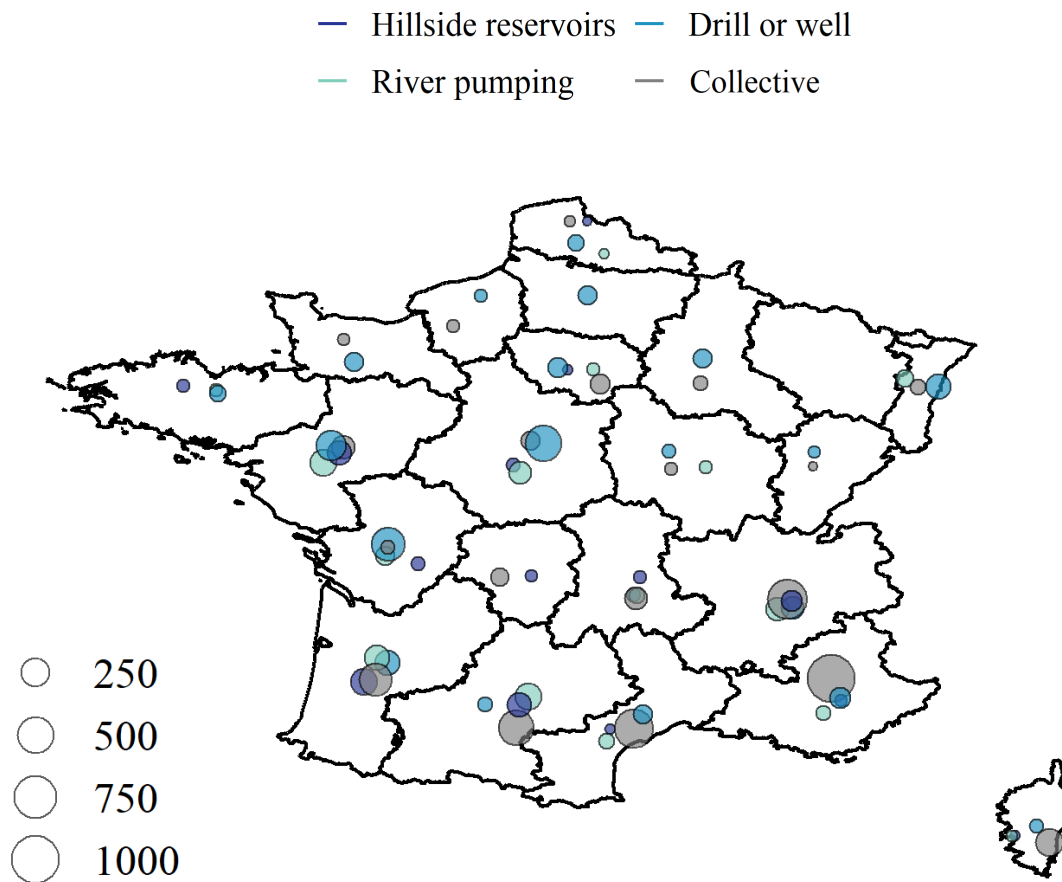
Table 2 presents the summary statistics for the variables on interest by type of irrigation. We include a test of mean differences between the group of farmer using collective irrigation and those using individual irrigation. We see that water charges are higher for farmers in the collective system, whereas energy charges are higher among farmers in the individual system. In average, energy costs make about 97% of these variables cost for farmers using individual irrigation, while only 39% for farmers using collective irrigation.

In Figure 2 we can see the geographical distribution of farms by type and source of irrigation. In almost every region we find farmers on both types of irrigation systems, which ensure that the results are not solely due to regional specificity. Farmers are also evenly distributed according to age and in a techno-economic orientation (see appendix B).

6.2 Irrigation and energy use in France

Figures 3 and 4 present the average distribution of variable costs (water and energy) of French farmers and their evolution between 2006 and 2011.

Figure 2: Geographic distribution of French farmers by type and source of irrigation

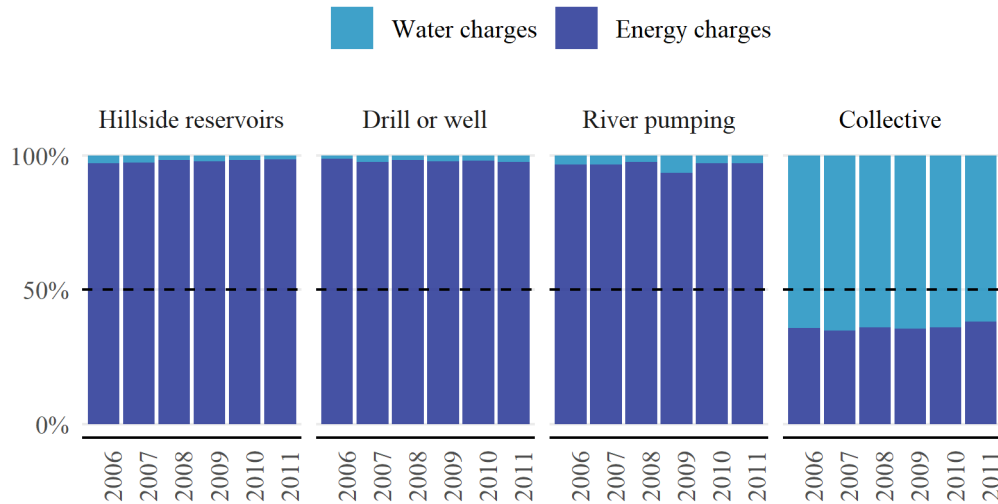


Source: FADN

The charges are presented by type of irrigation. Between 2006 and 2011, energy costs (mainly electricity) for French farmers contributed 30% to 90% to variable costs, water and energy (Figure 3). Energy costs have a lower weight among farmers attached to collective irrigation networks, representing on average 30%.

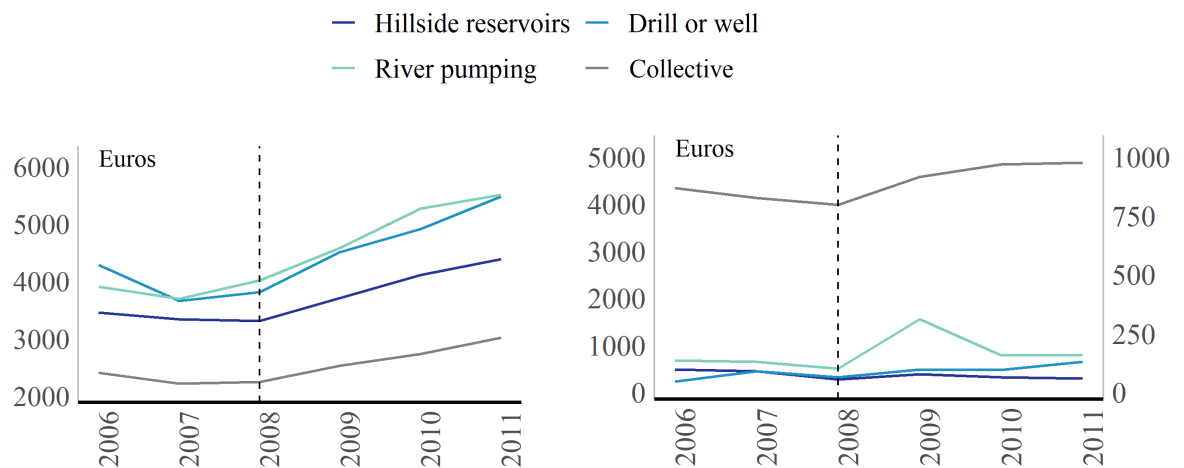
In France, the cost of water under an individual irrigation system is 20 to 50% lower than that of collective networks. This explains the significant weight of the water charges in the reference group. Furthermore, collective irrigation systems are older and therefore less energy consuming (Garin et al., 2013). For the rest of the farmers, energy costs take more than 90%. These irrigation systems need water pumping equipment. The farther away the water source is from the plot, the greater the amount of energy required for irrigation.

Figure 3: Average distribution of water and energy variable costs 2006-2011, by type and source of irrigation



Source: FADN

Figure 4: Evolution of average water and energy costs 2006-2011, by type and source of irrigation



(a) Energy charges

(b) Water charges

This Figure shows the water and energy charges of farmers in the sample between 2006 and 2011. The left panel presents the energy charges of all the farmers. The right panel shows the water charges. The y-axis on the left concerns the expenses of the farmers using collective irrigation. The y-axis on the right concerns the expenses of the farmers using individual irrigation.

Source: FADN

The deterioration of the economic situation since 2008 had an impact on the price of energy. We notice that after 2008, all farmers experienced an increase in the average energy costs. However, the trend of water charges increase in the reference group while remaining more or less stable for everyone else (Figure 4). This seems to support the leading hypothesis of this chapter, namely, that the cost effect, mostly bore by farmers using individual irrigation, induce them to reduce the water demand.

7 Estimation results

In this section we present the estimation results of the model presented above. We use iterated SUR to obtain consistent estimators, regardless which share equation is excluded from the system. Overall, model (17) has 59 parameters to be estimated. With the homogeneity and symmetry restriction, the number of parameters to estimate decreased to 49. The performance of the model improved significantly. We estimate this system in the software R, using the package `systemfit` and the option SUR with iterations (Henningsen, Hamann, et al., 2007).

Table 3 presents the parameters estimated from model (17). Standard error are reported in parenthesis. These model test the existence of a significant cost effect that induce farmers to reduce their demand for water.

We estimated three models. The first model does not include variables for subsidies. The second include a variable for investment subsidies, x_1 , and the third a variable for operating subsidies, x_2 . With these, we wanted to test if the subsidies may affect the estimate of the cost effect.

The results of the translog model suggests a cost effect with the expected sign and significantly different from zero for two of the individual irrigation groups. The model suggests that after a price shock, farmers having hillside reservoirs as irrigation source reduced their demand for water by 78% more than farmers in the collective irrigation network. Farmers using river pumping as their water source reduced their demand 27% more than farmers in the reference group.

Table 3: Model for farmer variable cost and demand for inputs, restricted model

| | Variable | <i>Iterated SUR Parameter Estimates</i> | | |
|-----------------------------------|---------------------------|---|------------------|------------------|
| α_0 | Constant | -14.10 (1.69)*** | -14.43 (1.69)*** | -16.64 (1.69)*** |
| α_w | $\ln p_{w,i}$ | -8.22 (0.55)*** | -8.40 (0.55)*** | -9.39 (0.54)*** |
| α_e | $\ln p_{e,i}$ | 9.22 (0.55)*** | 9.40 (0.55)*** | 10.39 (0.54)*** |
| α_y | $\ln Y_i$ | -1.05 (0.20)*** | -1.03 (0.20)*** | -0.80 (0.20)*** |
| β_{ww} | $\ln p_{w,i}^2$ | -0.77 (0.08)*** | -0.80 (0.08)*** | -0.96 (0.08)*** |
| β_{ee} | $\ln p_{e,i}^2$ | -0.77 (0.08)*** | -0.80 (0.08)*** | -0.96 (0.08)*** |
| β_{yy} | $\ln Y_i^2$ | 0.19 (0.01)*** | 0.18 (0.01)*** | 0.17 (0.01)*** |
| β_{we} | $\ln p_{w,i} \ln p_{e,i}$ | 0.77 (0.08)*** | 0.80 (0.08)*** | 0.96 (0.08)*** |
| β_{ey} | $\ln p_{w,i} \ln Y_i$ | -0.28 (0.02)*** | -0.28 (0.02)*** | -0.28 (0.02)*** |
| β_{wy} | $\ln p_{e,i} \ln Y_i$ | 0.28 (0.02)*** | 0.28 (0.02)*** | 0.28 (0.02)*** |
| α_T | D_T | 0.32 (0.53) | 0.32 (0.53) | 0.29 (0.53) |
| α_G^1 | D_G^1 | -36.42 (1.19)*** | -36.54 (1.18)*** | -35.92 (1.17)*** |
| α_G^2 | D_G^2 | -57.86 (0.86)*** | -57.90 (0.86)*** | -58.45 (0.85)*** |
| α_G^3 | D_G^3 | -55.57 (1.15)*** | -55.75 (1.15)*** | -56.26 (1.14)*** |
| α_{TG}^1 | $D_T D_G^1$ | -5.87 (1.42)*** | -5.93 (1.42)*** | -5.83 (1.41)*** |
| α_{TG}^2 | $D_T D_G^2$ | -0.99 (0.95) | -1.09 (0.95) | -1.02 (0.94) |
| α_{TG}^3 | $D_T D_G^3$ | -4.55 (1.28)*** | -4.60 (1.28)*** | -4.55 (1.27)*** |
| β_{wT} | $\ln p_{w,i} D_T$ | 0.05 (0.07) | 0.05 (0.07) | 0.06 (0.07) |
| β_{eT} | $\ln p_{e,i} D_T$ | -0.05 (0.07) | -0.05 (0.07) | -0.06 (0.07) |
| β_{yT} | $\ln Y_i D_T$ | 0.01 (0.03) | 0.01 (0.03) | 0.01 (0.03) |
| β_{wG}^1 | $\ln p_{w,i} D_G^1$ | -6.34 (0.15)*** | -6.33 (0.15)*** | -6.29 (0.15)*** |
| β_{wG}^2 | $\ln p_{w,i} D_G^2$ | -8.02 (0.12)*** | -8.05 (0.12)*** | -8.18 (0.12)*** |
| β_{wG}^3 | $\ln p_{w,i} D_G^3$ | -7.39 (0.15)*** | -7.42 (0.15)*** | -7.60 (0.15)*** |
| β_{eG}^1 | $\ln p_{e,i} D_G^1$ | 6.34 (0.15)*** | 6.33 (0.15)*** | 6.29 (0.15)*** |
| β_{eG}^2 | $\ln p_{e,i} D_G^2$ | 8.02 (0.12)*** | 8.05 (0.12)*** | 8.18 (0.12)*** |
| β_{eG}^3 | $\ln p_{e,i} D_G^3$ | 7.39 (0.15)*** | 7.42 (0.15)*** | 7.60 (0.15)*** |
| β_{yG}^1 | $\ln Y_i D_G^1$ | -0.21 (0.09)** | -0.19 (0.08)** | -0.24 (0.08)*** |
| β_{yG}^2 | $\ln Y_i D_G^2$ | 0.19 (0.05)*** | 0.19 (0.05)*** | 0.18 (0.05)*** |
| β_{yG}^3 | $\ln Y_i D_G^3$ | 0.28 (0.07)*** | 0.28 (0.07)*** | 0.25 (0.07)*** |
| α_{x1} | x_1 | | 0.02 (0.00)*** | |
| α_{x2} | x_2 | | | 0.00 (0.00)*** |
| <i>Cost effects</i> | | | | |
| β_{wTG}^1 | $\ln p_{w,i} D_T D_G^1$ | -0.78 (0.18)*** | -0.78 (0.18)*** | -0.78 (0.18)*** |
| β_{wTG}^2 | $\ln p_{w,i} D_T D_G^2$ | -0.11 (0.11) | -0.11 (0.11) | -0.12 (0.11) |
| β_{wTG}^3 | $\ln p_{w,i} D_T D_G^3$ | -0.27 (0.15)* | -0.27 (0.15)* | -0.28 (0.15)* |
| β_{eTG}^1 | $\ln p_{e,i} D_T D_G^1$ | 0.78 (0.18)*** | 0.78 (0.18)*** | 0.78 (0.18)*** |
| β_{eTG}^2 | $\ln p_{e,i} D_T D_G^2$ | 0.11 (0.11) | 0.11 (0.11) | 0.12 (0.11) |
| β_{eTG}^3 | $\ln p_{e,i} D_T D_G^3$ | 0.27 (0.15)* | 0.27 (0.15)* | 0.28 (0.15)* |
| β_{yTG}^1 | $\ln Y_i D_T D_G^1$ | 0.12 (0.10) | 0.13 (0.10) | 0.12 (0.10) |
| β_{yTG}^2 | $\ln Y_i D_T D_G^2$ | 0.02 (0.06) | 0.03 (0.06) | 0.02 (0.06) |
| β_{yTG}^3 | $\ln Y_i D_T D_G^3$ | 0.28 (0.08)*** | 0.29 (0.07)*** | 0.28 (0.07)*** |
| Eq VC Adj. R ² | | 0.23 | 0.24 | 0.26 |
| Eq ω_w Adj. R ² | | 0.76 | 0.76 | 0.76 |
| Observations | | 7906 | 7906 | 7906 |

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Farmers using a drill or well as water source did not reduce their demand significantly more than farmers in the reference group (collective). As we can see in Figure 4b, there is a peak for this group after 2008.

The coefficient for the time variable (after the price shock) α_T is not significant, which is consistent with the expectation that the price shock had no effect in the demand for water of farmer in using collective irrigation systems.

The coefficients α_G^k capture the difference in water demand in absence of price shock. We can see that this difference is significant and suggests that even in absence of a price shock, farmers using individual irrigation systems (regardless of the source of water) have a lower demand for water than farmers in the reference group.

This seems to indicate that there is no rebound effect. Meaning that the improvement of the irrigation technology actually helps to reduce water consumption. Nevertheless, we cannot be sure of it, since the model provides further evidence on the existence of a cost effect derived from the use of more efficient (and energy-intensive) irrigation technologies.

Furthermore, it suggests that even though an efficiency improvement may contribute to water economies, it leads to a higher consumption on energy which in turn contribute to CO₂ emissions. In other words, there seems to be a trade-off between water economies and CO₂ emissions reductions.

We see that subsidies have a small, but positive and significant effect on the production function. The cost effect remains unchanged after controlling for subsidies.

8 Conclusions

In this chapter, we propose a theoretical model for water demand, in which we model the irrigation cost as a function of the price of energy. The goal of this modeling was to identify the factors that ensure the effectiveness of "green irrigation". Furthermore, we test the model empirically on accountancy data from French farmers (FADN) between 2006 and 2011.

The results of the theoretical model presented in this chapter support the existence of a rebound effect not only due to water, but also due to energy. The improvement in irrigation efficiency produces three effects: an income effect as a result of the technical improvement, since, all other things being equal, an increase in efficiency allows the farmer to save more (expend less in) water, which leads to an additional income. A second effect, the productivity effect, is related to the fact that the same amount of water applied more efficiently increases crop yields. Finally, the third effect affects the cost of irrigation. A more efficient irrigation system requires more energy to operate, which increases energy costs.

The productivity and income effects contribute to the accentuation of the pressures on water resources. The cost effect, meanwhile, is positive in terms of water conservation, but contributes to the emission of greenhouse gases linked to the intensive use of non-renewable energies. This shows the importance of taking into account the "water-energy nexus"⁸ when discussing efficient irrigation technologies in agriculture and water conservation policies.

Furthermore, we implement an empirical model to test the theoretical findings. We approximate the farmer's production function by a translog function with interactions between time and irrigation type. We argue that farmers will react similarly to a price shock than to an increase of energy costs after an efficiency improvement. Thus, we implemented a methodology that exploits the variation of energy charges in our dataset, which includes the price shock of 2008-2009, to test the effect of a price shock on water demand.

The reference group is formed by farmers attached to a collective irrigation network. Collective irrigation systems tend to be older and therefore less energy consuming, implying that they will be less affected by the shock on energy prices, as confirmed by the empirical model. Furthermore, due to higher investment costs, these systems are not frequently renewed (i.e. efficiency). These characteristics make of this group a good counterfactual for water demand after a price shock.

⁸Water-Energy-Food Nexus, United Nations.

On the other hand, farmers using private (individual) irrigation systems require a pumping device to transport the water from the source to the plot. The amount of energy required to irrigate the crops is mainly determined by the distance from the source to the plot. We have three different categories depending on the source of the irrigation water. Each of these sources has distinct properties (i.e. depth, distance to plot, elevation). Therefore, the efficiency of application and the energy needs may differ.

The results of the translog model show a significant and negative cost effect for two of the three irrigation categories. The model suggests that after a price shock, farmers having hillside reservoirs as irrigation source reduced their demand for water by 78% more than farmers in the reference group. Farmers using river pumping as their water source reduced their demand 27% more than farmers in the reference group.

The difference in water demand previous to the price shock is significant and suggests that even in absence of a price shock, farmers using individual irrigation systems (regardless of the source of water) have a lower demand for water than farmers in the reference group. This seems to indicate that there is no rebound effect. Nevertheless, we cannot be sure of it, since the model provides further evidence on the existence of a cost effect derived from the use of more efficient (and energy-intensive) irrigation technologies.

Furthermore, it suggests that even though efficiency improvements may contribute to water economies, this is achieved through a higher consumption on energy which in turn contribute to CO₂ emissions. In other words, there seems to be a trade-off between water economies and CO₂ emissions reductions.

The results of this work contribute to the literature on the water-energy nexus, suggesting that previous studies did not take into account the impact on the energy charges linked to the improvement of the efficiency. The water savings (absence of rebound effect) sometimes observed in the literature are more likely due to the increase in energy cost and not to the improvement in the efficiency of irrigation.

Moreover, we show that a perverse effect of green irrigation is the increase in energy use. As the source of this energy is generally non-renewable, green irrigation can contribute to

the increase in greenhouse gas emissions.

Theoretically, subsidies, for the adoption of technologies or for energy costs, will further strengthen the rebound effect. They compensate for the increase in energy charges and allow the farmer to increase water use. The empirical application, show no effect of subsidies on the cost effect, although it suggest a positive relationship with demand. This result does not imply that subsidies should be avoided. It points out that policymakers must ensure that subsidies do not lead to a trade-off between water savings and energy savings.

It is necessary to better coordinate the goals of environmental policies when it comes to water and energy, so that these can be simultaneously achieved and not canceled out. Pilot projects are already underway to develop the use of green energy in irrigation. To date, they are still not suitable for all territories.

Appendices

A Energy consumption by irrigation technology

Irrigation systems consume energy to operate the pump that delivers water from the source to the field. One of the most energy intensive components is the pressure level used in the system. The choice of the pressure level in irrigation systems can be a source of energy savings. However, a low pressure level can lead to a less efficient application of water and it may even deprive crops of the resource (not enough pressure to extract the resource) (Belaud et al., 2020). The literature then suggests the existence of a trade-off between the use of water and energy (Monforti-Ferrario and Pascua, 2015).

The modernization of irrigation systems implemented by the Spanish government in the early 2000s, aimed at converting the old open channel distribution infrastructure into pressurized pipe networks and to achieve annual water savings (Berbel et al., 2015). Research has shown that the demand for water per unit of irrigated area has fallen by just over 20% from 1950 levels. However, the demand for energy is said to have increased by 149% over the same period (Fernández García et al., 2014).

Espinosa-Tasón et al. (2020) analyze the evolution of water and energy consumption in the south of Spain between 1950 and 2017. In particular, they take into account the average efficiency of irrigation and estimate the consumption of unit average energy. The Table 4 presents the result of their estimation.

Table 4: Estimation of energy consumption by level of irrigation efficiency in Spain between 1950 and 2017

| | 1950 | 1960 | 1980 | 2004 | 2013 | 2017 |
|---------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Irrigation efficiency | 0.6 | 0.6 | 0.64 | 0.76 | 0.79 | 0.8 |
| Energy kWh/m ³ | 0.03 | 0.03 | 0.08 | 0.1 | 0.14 | 0.17 |

Source : Espinosa-Tasón et al. (2020).

They consider three types of irrigation: surface irrigation; sprinkler irrigation, introduced around 1967, and micro-irrigation or drip irrigation, introduced in 1981. The average efficiency of each of these systems is 60%, 80% and 90% respectively. Currently, 51% of

irrigated land uses the micro-irrigation method.

Between 2005 and 2013, the irrigation efficiency increases by 0.4% while the energy consumption per m^3 increases by 2.2%. Between 2014 and 2017, these same indicators increase by 0.3 and 4.5%, respectively. The micro-irrigation (the most efficient) becomes the most used after 2005 and the energy consumption per m^3 is the highest during this period.

Other studies measuring the unit of energy consumption are in line with the results of the Spanish case. The most efficient irrigation systems are often associated with higher energy consumption.

The Table 5 presents a summary of results measured in Australia (Jacobs, 2006).

Table 5: Estimation of energy consumption by irrigation system

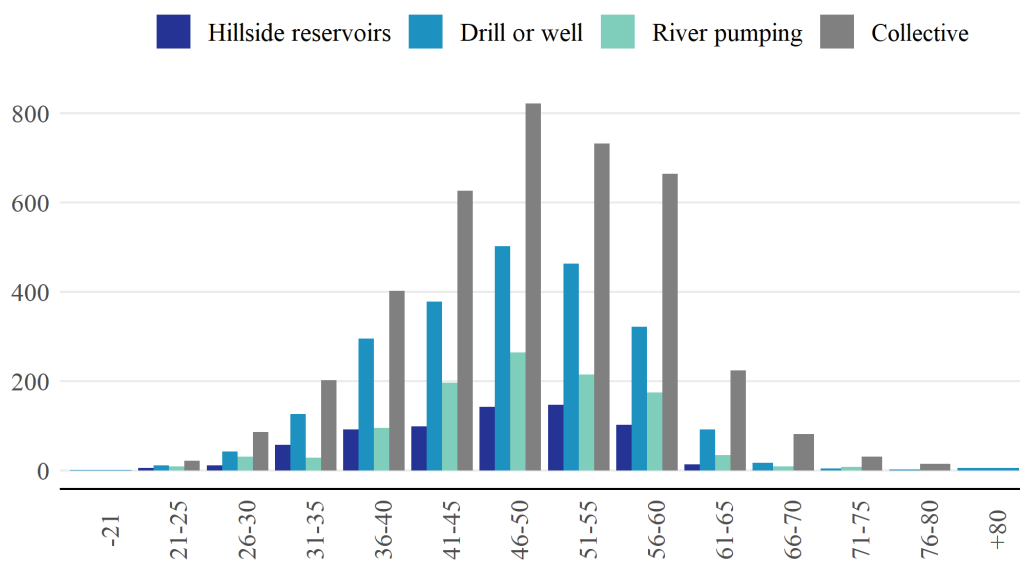
| Source | Irrigation system | Efficiency | Energy consumption |
|---------------|--------------------|------------|------------------------------|
| Jacobs (2006) | Irrigation surface | 50-70% | 2.16 GJ/ha/year ^a |
| | Micro-irrigation | 70-95% | 3.72 GJ/ha/year ^a |
| | Pivot | 75-85% | 3.92 GJ/ha/year ^a |

GJ/ha : Gigajoule par hectare.

Jacobs (2006) finds that the energy consumption associated with the operation of the irrigation system is between 72% and 81% higher under pivot or micro-irrigation systems than under a surface irrigation system.

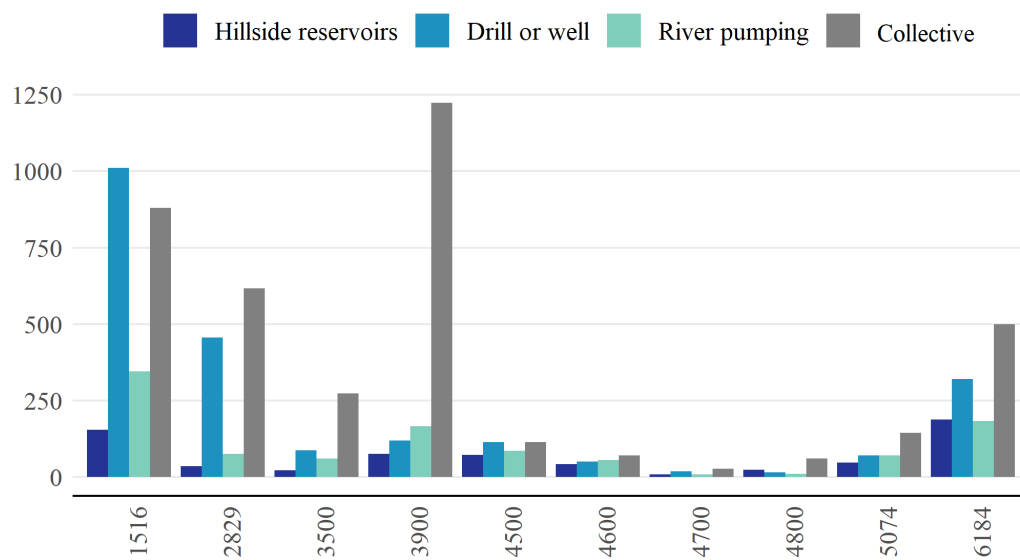
B Farmers characteristics

Figure 5: Farmers age distribution by type and source of irrigation



Source: FADN

Figure 6: Farmers distribution by techno-economic orientation and type and source of irrigation



Source: FADN

Conclusion

The current warming level at 1°C has already altered people, livelihoods and natural ecosystems all around the world. The planet has faced extreme weather events, biodiversity loss and sea level rise cause unprecedented risks, specially to the most vulnerable communities. If the current warming rate is not stopped, global warming is likely to reach 1.5°C in the next 10 to 30 years. What is more, greenhouse gas emissions need to decline rapidly by 2030, to avoid warming to surpass 1.5°C in the following decades.

Despite the enormous progress made in mitigation and adaptation policies over the last few decades, the speed of these achievements is still behind the progression of global warming. Limiting warming to 1.5°C will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally.

Efficiency improvement policies constitute an important pillar of climate change mitigation and adaptation. They have been a determinant factor in the achievement of the EU 2020 targets. On the mitigation side, energy efficiency policies aim a decreasing carbon emissions from vehicle use and residential building. On the adaptation side, it has been applied to irrigation water for preventing water depletion. In these sectors is where we find the greatest the potential for savings.

However, the economic literature has observed the existence of the rebound effect, an unintended result arising from individual behavior adjustments following an efficiency improvement. The rebound effect can decrease the effectiveness of mitigation and adaptation strategies that are based on efficiency improvements.

Evidence of the rebound effect has been found in the use of vehicle and in residential

energy services, with efficiency losses going from 5% to 25% in vehicle fuel, in some European countries it up to 80%. For heating, it ranges between 30% and 70%.

In agriculture, empirical results show that programs of improvement in irrigation technology have ambiguous effects on water use and do not systematically reduce water demand. Some do not find evidence a rebound effect, whereas other find rebound going from 64% to more than 100%, mainly due to an increase in the irrigated land. In this case however, there are more elements at play. Water demand may also decrease due to the higher energy costs linked to a more efficient irrigation system, and this at the expense of higher greenhouse gas emissions coming from the increase in energy use.

This thesis make a number of contributions to the literature from a theoretical and an empirical point of view on a micro-economic level.

We test the sensibility of the estimates of the rebound effect to the methodology. We proposed a new methodology that accounts for potential selection bias of multi-vehicle households. We provide further evidence on the existence of heterogeneous rebound that depend on the number of vehicles and the the level of efficiency of the vehicles (quadratic effects).

We proposed a new theoretical framework, based in the theory of the collective household, to estimate the rebound effect by accounting heterogeneous preferences inside a household. We find evidence supporting the importance of heterogeneity in the measure of the rebound.

We provide further evidence on the existence of indirect cross-resource rebound effects present in the sector of agriculture. When controlling for the level of efficiency, we show that farmers using a more irrigation efficient technology do reduce their water consumption, however, this is not a result of the higher efficiency but a consequence of the higher energy charges associated to it. This gives us insight into the nexus water-energy and the existence of what we called cross-resource rebound effects.

Our findings stress the importance of considering the rebound effect in the design of

efficiency improvement policies. The existence and the magnitude of the rebound effect therefore present a critical challenge for environmental sustainability.

This thesis reinforces the argument that rebound effects could be larger than many previous studies have found. Our results support the key role of heterogeneity when, for instance, we take into account differences in preferences in the households.

Four key policy results are drawn from this thesis.

First, individuals (households and farmers) adapt their consumption decisions after major shift that alters relative prices, for instance, an efficiency improvements. This may go against the expected results of climate mitigation and adaptation policies, which could explain why these policies have fall short of the climate objectives in some sectors such as transportation and agriculture.

Second, these adjustments are not homogeneous across households. Their response depends on the characteristics of their energy consuming devices (e.g. vehicle) and the socio-economic characteristics such as geographic zone, income or age.

Third, currently there is to some extent an incompatibility of climate adaptation policies, such as those aiming at generate water savings and climate mitigation policies, those aiming at reducing the CO₂ emissions. So far, adaptation policies have shown promising results in water savings, however these may have been achieved at the expense of higher CO₂ emissions.

Fourth, the economic situation is important. In the case of farmers, price shocks alter their production costs which can alter the impact of environmental policies on water conservation.

Our final policy recommendations can be summarize in five points.

In order to achieve the climate goals set in the Paris agreement, climate mitigation policies have to be designed hand in hand with climate adaptation policies as to maximize their impact instead of neutralize it. Policy-makers should better coordinate the goals of environmental policies when it comes to water and energy.

Policy design have to consider potential behavior adjustments, namely the rebound effect, that may reduce the positive impact on the environment. Efficiency policies should be coupled with complementary measures, such as differentiated taxes or resource regulations, in order to counter the rebound effect and achieve the desired environmental outcome.

Furthermore, policies should to account for heterogeneity. Better targeted policies can maximize the positive impact on the environment while balancing the burden supported by citizens. Unique instruments usually do not have the same strength and may ultimately contribute to widespread problem of acceptability of public policies.

The economic situation, should be taken in to account and policies should be adapted to it. Periods of crisis, such as the current one, in which a raging virus has forced individuals to change their behavior and adapt their preferences, should be taken as an opportunity to encourage long-lasting behavioral changes.

Ultimately, the success of climate policies is a matter of behavior and acceptability. A major result of the thesis is the theoretical and empirical demonstration of the importance of taking into account individual heterogeneity. Also, to improve the effectiveness of policies, it is crucial that the policy can target individual profiles. This targeting would make possible to optimize the effects of the policy and increase its acceptability.

From a practical point of view, these policies can include incentive policies such as differential taxes, or behavioral policies, such as targeted diffusion of information on the effects of climate change on a daily basis.

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Titre : Amélioration de l'efficacité et changement climatique : quelles politiques énergétiques ?

Mot clés : Effet rebond, Efficacité énergétique, Consommation d'énergie, Ménage collectif, Eau d'irrigation, Aide à l'investissement.

Résumé : L'augmentation de l'efficacité d'un système est souvent considérée comme un moyen de réduire l'utilisation intensive des ressources naturelles. Paradoxalement, les améliorations techniques n'impliquent pas nécessairement des économies de ressources. La littérature économique a observé des ajustements dans le comportement des producteurs et des consommateurs après de telles améliorations, ce qui se traduit souvent par une demande accrue de la ressource, un effet opposé à celui visé par la politique. L'augmentation de la demande suite à une amélioration de l'efficacité technique d'un dispositif est connue sous le nom d'effet rebond. Cette thèse est structurée en trois chapitres

combinant à la fois des méthodes théoriques et empiriques pour aborder différents aspects de l'effet rebond dans la demande d'énergie et d'eau. Le premier chapitre présente une analyse empirique qui compare les différentes méthodes utilisées pour estimer l'effet rebond dans l'utilisation du véhicule privé. Le deuxième chapitre propose un nouveau cadre théorique d'analyse de l'effet rebond, fondé sur l'hétérogénéité des ménages, qui peut être utilisé pour estimer l'effet rebond résidentiel et de la voiture personnelle. Le dernier chapitre évalue l'effet rebond dans l'utilisation de l'eau d'irrigation et examine les implications de la relation existante entre la demande d'eau d'irrigation et la demande d'énergie.

Title: Efficiency improvement and Climate change: what energy policies?

Keywords: Rebound effect, Fuel efficiency, Energy consumption, Collective Approach, Irrigation Water, Investment aid.

Abstract: Increasing a system efficiency is often seen as a cost-effective way to reduce intensive use of natural resources. Paradoxically, technical improvements do not necessarily imply resource savings. Economic literature has observed adjustments in producers and consumers behavior after such improvements, which often results in increased demand for the resource, an opposite effect to that intended by the policy. The increase in demand following an improvement in the technical efficiency of a resource conversion device, is known as the rebound effect. This thesis is structured in three chapters combining

both theoretical and empirical methods to address different aspects of the rebound effect in energy and water use. The first chapter presents an empirical analysis that compares the different methods used to estimate the rebound effect in the use of the private vehicle. The second chapter proposes a new theoretical framework of analysis for the rebound effect, based on households heterogeneity, that can be used to estimate residential and vehicle use related rebounds. The final chapter evaluates the rebound effect in the use of irrigation water and discusses the implications of the existing relation between irrigation water demand and energy demand.